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CONTROL TECHNOLOGY FOR FINE PARTICULATE EMISSIONS

Midwest Research Institute

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May 1974

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ABSTRACT

This report gives results of a study to assess the state of the art of control technology for fine particulates emitted from stationary sources. It emphasizes the analysis of control technology for primary particulates. The initial activity was a general review of collection and agglomeration mechanisms for particulates. Both theoretical and experimental facets were reviewed with attention on forces or collection mechanisms expected to be of importance for fine particles. The analysis of control technology for fine particulates centered on conventional control equipment, on emerging control technology, and on proposed or conceptual control systems.

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A E Vandegrift
for H. M. Hubbard, Director
Physical Sciences Division

CONCLUSIONS

Presently available equipment for the control of particulate emissions from stationary sources has achieved limited success in the control of fine particulate pollutants (i.e., less than or equal to 3 micron diameter particles). The inability of existing control equipment to collect the fine particulates means that if we are to achieve significant control in this area an aggressive, well-conceived research and development program will be required to improve existing equipment and develop new techniques for the collection of fine particulates.

In order to assist EPA in formulating an overall R&D program on control technology for fine particulates, Midwest Research Institute (MRI) conducted an assessment of the current and future potential for the control of fine particulates under the auspices of the Air Pollution Control Division, Office of Research and Development, Environmental Protection Agency. The major areas included in the evaluation were:

1. Particle collection and agglomeration mechanisms or forces that may be effective in the submicron size range;

2. Conventional control equipment for particulates; and

3. Emerging or proposed control devices that appear promising, but have not been reduced to practice on a commercial scale.

The principal results of our assessment are presented in the following subsections.

PARTICLE COLLECTION AND AGGLOMERATION MECHANISMS

The review of collection and agglomeration mechanisms for particulates served to pinpoint approaches and underlying mechanisms or forces which have potential for use in the control of fine particulates. Table 1 lists the approaches that appear to have significant potential. While

Table 1. PROMISING APPROACHES FOR COLLECTION OR AGGLOMERATION OF FINE PARTICLES

I. Particle collection

   A. High velocity differential between fine particles and collector bodies

   B. Low velocity differential between fine particles and collector bodies with both particles and collector bodies charged

   C. Electrostatic and diffusiophoretic forces

II. Agglomeration and/or particle growth

   A. Electrostatic agglomeration

   B. Sonic agglomeration

   C. Condensation

the approaches delineated in Table 1 offer possibilities for use with fine particles, realization of the potential will require the development of viable control systems. In some instances, it may be possible to modify or redesign conventional control systems to take advantage of the promising mechanisms. Alternatively, new control systems will have to be developed. Some avenues that might be pursued to utilize the approaches suggested in Table 1 are discussed next.

High Velocity Differential Systems

Systems utilizing high velocity differentials between the particles and collector bodies would achieve particle collection by inertial impaction. In order to achieve 90% single particle target efficiency* for particles in the 0.1-1.0 micron particle size range, velocity differentials in the range of 10^2-10^4 m/sec and collecting bodies of diameter 50 microns or less are required. Velocity differentials of that magnitude can generally be achieved for less energy expenditure by imparting the high velocity to the collector bodies rather than the gas stream. Since the velocity differential required to attain a given target efficiency decreases with decreasing size of the collector body, the technique employed to achieve the high velocity of the collector body should also generate the smallest collection bodies possible.

Systems utilizing small, high velocity water drops as the collecting bodies are the most practical. Conventional venturi scrubbers operate on this principle, but the energy requirements (i.e., pressure drop) for fine particle collection are high. Techniques to generate the small, high velocity water drops at a lower energy expenditure are needed.

Nozzle(s) configurations which can both accelerate and shear the water stream into small drops should be investigated. The wet scrubbing systems developed by Lone Star Steel and Aronetics, Inc. (see Appendix B) represent new control systems that employ small, high velocity water drops for particle collection. Both of these systems use waste process heat rather than external energy to provide the energy required to establish the requisite particle-droplet differential velocities and move the gases through the system.

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* Single particle target efficiency is defined as

$$\eta = \frac{\text{cross-sectional area of fluid stream from which particles are removed}}{\text{cross-sectional area of filter element projected in direction of flow}}$$

Low Velocity Differential Systems

Low velocity differential systems of several configurations might be used to collect fine particles--especially if electrostatic forces are utilized to augment the other collection forces. Electrostatic forces might be used advantageously for cleaning gases because they can be significantly greater than mass forces. Fabric filters, wire mesh filters, granular beds, or fluid beds could be used as the underlying filter elements.

Theoretical and limited experimental studies have shown that electrostatic forces can improve the collection efficiency of the filter systems mentioned in the preceding paragraph (see Appendices F, G, and H). To date, experimental studies of electrified filters have been confined to laboratory-scale equipment or clean, high porosity systems. It is not clear whether the improved performance of electrified filters noted in the laboratory scale equipment can be realized in commercial-scale equipment under actual industrial gas cleaning conditions. Also, it is not certain that any increase in collection efficiency which might be realized in commercial-scale equipment will be sufficient to justify the use of electrified filters. Additional R&D will be required to answer these questions.

Electrostatic Forces

Electrostatic forces between charged particles and collecting bodies are quite effective for the collection of particulates. To secure rapid and efficient deposition of particles, forced charging of particles should be used. Electrostatic precipitators and various types of electrified filters (see preceding section) can be used to take advantage of electrostatic forces for particle collection.

Particle migration velocities calculated from theoretical equations for field and diffusion charging indicate that migration velocities in the range of 2 cm/sec should be realized for fine particles in electrostatic precipitators operating with reasonable electric fields, charge densities and residence times. Therefore, significant collection of fine particulates should be possible in electrostatic precipitators.

Diffusiophoretic Forces

The diffusiophoretic force, which is a combination of forces due to Stefan flow and a concentration gradient, should be a useful force to exploit in collection of small particles. The fundamental mechanism is not sensitive to particle size and becomes more important compared to other removal mechanisms for particles below 2 microns. To exploit the mechanism of diffusiophoresis, the collecting device must be designed such that one component in the gas phase is diffusing toward a collecting surface. The most practical case is the diffusion of water vapor toward a surface. Recent studies (see Appendix C) indicate that diffusiophoresis can produce appreciable particle deposition under the heat and mass transfer conditions of a realistic wet scrubber.

AGGLOMERATION AND/OR GROWTH OF PARTICLES

The agglomeration or growth of fine particles, as a step in the control of fine particulates, is in principle attractive. If large particles can be produced for reasonable energy expenditures, it may be possible to utilize devices which cause particle agglomeration or growth in conjunction with conventional control systems.

Condensation is the most feasible way to achieve particle growth without agglomeration. However, rather than utilize a separate chamber to grow particles via condensation, incorporation of condensation effects directly into wet-scrubber systems is recommended.

A potential way to agglomerate fine particles to a larger size is to pass the aerosol through a sonic field. Sonic fields can effectively induce agglomeration in all sizes and types of particulate materials. However, the minimum particulate loading that can be treated is about 1.1-2.3 g/m^3 (0.5-1.0 $grains/ft^3$). For more disperse systems it is necessary to seed the gas to bring the particle loading up to the requisite level.

The addition of a bipolar charge to an aerosol can produce a significant increase in the rate of agglomeration of submicron particulates. A bipolarly charged polydisperse aerosol containing a large number of relatively large particulates, as well as fine particulates, appears to be the most favorable situation because it may be possible to collect numerous fine particulates on the large particulates before charge annihilation occurs.

CONVENTIONAL CONTROL EQUIPMENT

Well-designed conventional control systems are capable of achieving relatively high collection of fine particulates. However, more often the performance of conventional devices is less than satisfactory. The poor performance of most conventional equipment results from:

1. Inherent limitations of conventional equipment in the fine particle size range; and

2. Lack of previous need to control fine particulates and the resultant lack of interest in optimizing systems with emphasis on the collection of fine particulates.

Item 1 results from the fact that the mechanisms or forces exploited in a specific device are not effective in the fine particle size range. The second item, which is only applicable to control systems not inherently limited by the forces or collection mechanisms utilized in the systems, is a result of previous priorities established for the control of particulate emissions.

Although conventional control equipment is often not very effective for collecting fine particles, certain types of devices can be quite effective--especially if their performance is optimized for fine particulates. High efficiency electrostatic precipitators offer considerable potential in this regard. Changes within the present state of the art (i.e., increases in the collection area to volume ratio, charge density, and field strength) could produce significant improvement in the collection of fine particulates from some sources. Consideration should also be given to the further development of wet electrostatic precipitators--especially for use with high resistivity dusts.

Improvements in fabric filter technology might also result in better control of fine particles from some sources. Avenues to pursue to improve performance are not as clear-cut as with electrostatic precipitators. Improvements in fabric filters which would permit their use on a wider spectrum of emission sources would be an important advance.

Improvements in the performance and reduction in power consumption of venturi or orifice type wet scrubbers might be achieved by taking advantage of condensation effects which can occur in these types of wet scrubbers. Improvements in low energy scrubbers could result from the enhancement of the contribution of flux forces (i.e., diffusiophoresis, thermophoresis, condensation).

EMERGING AND PROPOSED CONTROL SYSTEMS

In the category of emerging and proposed control systems for fine particulates, there are several systems that hold promise for transition to commercially viable systems. At the present time, foremost in the category of emerging systems are the Steam-Hydro Air Cleaning and the ADTEC wet-scrubbing systems. Both of these systems appear applicable to a wide range of sources, but economics will probably limit their use to sources where waste heat is available. Where waste heat is not sufficient to meet the power requirements of the systems, supplemental heat may be used. However, the use of supplemental heat would add significantly to the overall cost of both systems.

Only limited data from laboratory-scale systems are available to judge the potential of most of the proposed systems. Assessments must be based predominantly on the ability of the underlying collection forces or mechanisms to collect fine particulates. Condensation scrubbers, charged droplet systems, electrified filters of various types, and foam scrubbers have sufficient potential to merit additional research and development. Future studies on any of the promising proposed systems should be conducted in equipment configurations and sizes that will produce reliable engineering design data.

RECOMMENDATIONS FOR R&D PROGRAMS

Control technology for fine particulates is at a very early stage of development and well-conceived research and development programs are needed to improve and develop equipment for the collection of fine particulates. Our review identified several areas we recommend as the subjects for additional investigation. The Environmental Protection Agency through its Control Systems Laboratory has initiated a program on fine particulate control technology and some of the elements of the EPA program involve some of the areas we identified as subjects for future research.

Recommendations for research programs in the areas of collection and agglomeration mechanisms for particulates, conventional control systems, and emerging and proposed control systems are discussed next.

COLLECTION AND AGGLOMERATION MECHANISMS

The review of collection and agglomeration mechanisms for particulates served to pinpoint approaches and underlying mechanisms or forces which should have potential for use in the control of fine particulates. Table 1, page 2 lists the approaches that have significant potential. The parametric dependence of many of the mechanisms or forces underlying the approaches listed in Table 1 are not well-defined and additional research is warranted to develop requisite data. Specific program areas are discussed in the following subsections:

Studies of the Dynamics of Particulate Agglomeration

Small particles suspended in a gas can be subjected to a variety of forces (e.g., thermal, electrical, sonic) which may cause them to come together and form agglomerates. Since particle agglomeration may occur as a step in a control system for fine particulates, a better understanding of the dynamics of particle agglomeration under conditions suitable to industrial gas cleaning applications is needed. There are likely to be a number of factors of importance to the agglomeration process in specific cases. In the case of charged aerosols, electrostatic forces dominate and thus control the course of agglomeration. For situations where steam is present, condensation phenomena may control the process.

Identification of the dominant parameters in the agglomeration process in specific cases of practical interest should be the objective of the program. Once the important parameters are delineated, methods for enhancing the agglomeration of fine particles should be defined and tested in bench-scale equipment.

Sonic Agglomeration

Sonic fields are an effective way to agglomerate particulates. Sonic precipitators were tested extensively in the 1950's, and were shown to effectively agglomerate very fine particulates. These first-generation devices used a sonic field to agglomerate fine particulates to a minimum mean diameter of 10-15 microns. The resulting particulates were then removed from the gas stream by a conventional cyclone. These early sonic agglomerators had relatively large energy requirements--typically 0.2-0.4 hp/m^3/min (5-10 hp/1,000 cfm).

The rate of agglomeration of particulates in a given sonic field is, to a reasonable approximation, directly proportional to both the residence time and the square of the particle density. Consequently, if the required size of the final agglomerate could be reduced by an order of magnitude, the energy requirements would be reduced by more than an order of magnitude. This reduction in required size could be achieved by the use of an electrostatic precipitator to collect the agglomerates in place of the cyclones previously used. As a consequence, total energy requirements of 0.04-0.08 hp/m^3/min (1-2 hp/1,000 cfm) or even less might be attainable.

Work needs to be done to determine the energy required to agglomerate various particulates to 1-2 micron mean diameter in sonic fields and the resulting size distributions. The efficiency with which electrostatic precipitators can handle the agglomerated particulates also needs to be determined since many "sonic agglomerates" have been reported to be rather easily disintegrated.

Theoretical and Experimental Investigation of the Dynamics of Mixing of Steam, Water Droplets and Particulates

Steam and/or water drops can play an important role in enhancing several collection mechanisms that might be exploited to improve the collection of fine particulates (e.g., diffusiophoresis, steam condensation). At present, there is little more than an order of magnitude quantitative understanding of the phenomena occurring when steam, water droplets and particulates are mixed. This is especially true in equipment configurations that are likely to be useful in actual industrial gas cleaning applications.

The dynamics of the mixing process should be studied from both a theoretical and experimental standpoint. Factors to be studied should include the dynamics of mixing, nucleation phenomena, heat and mass transfer rates and droplet and/or particle growth. Configurations to be studied should include cooled wall condensors, converging-diverging nozzles, sieve-plates, jets and pipeline scrubbers. The main thrust of the investigations should be directed to the generation of basic information that will result in design equations for steam injection and mixing systems.

Particle Charging

The effectiveness of electrostatic forces for either particulate collection or agglomeration is directly dependent upon the charge acquired by the particulates. Theory and experiment show that the failure of particle charging systems to highly charge fine particles causes poor fine particle collection in any electrical gas cleaning process.

Additional research on fine particle charging is recommended in order to achieve the inherent potential of electrical gas cleaning processes. Both theoretical and experimental research on fine particle charging is recommended because present theories do not adequately describe fine particle charging and existing experimental data are not representative of actual gas cleaning systems. Emphasis should be placed on the development of charging systems that are practical for use with the various types of electrostatically augmented control systems currently available or under development.

CONVENTIONAL CONTROL EQUIPMENT

Conventional control equipment can play a significant role in the control of fine particles--especially if the inherent potential of certain types of devices can be realized. Attainment of the full potential of conventional control equipment will require additional research. Recommended areas of investigation are delineated below.

Electrostatic Precipitators

Theoretical studies and recent field testing have indicated that electrostatic precipitators can be more effective for the removal of submicron particulates than previously assumed. Additional study of electrostatic precipitators is recommended with effort focused on field evaluations, to define their true potential for fine particulate collection on a variety of industrial sources.

Because the electrical characteristics of particulates emitted from many sources fall outside the range where capture by dry electrostatic precipitators is most effective, research on wet electrostatic precipitators is also recommended. Initial effort on wet electrostatic precipitators should involve a detailed feasibility study followed by field evaluation tests on existing installations.

Fabric Filters

On those sources where they can be used, fabric filters are excellent control devices for fine particles. Improvements in fabric filters which would permit their use on a wider spectrum of emission sources would be an important advance. Recommended research topics are: (1) feasibility study of fabrics composed of finer fibers; (2) investigations of techniques for tailoring of "active area" of filter fabric; and (3) high temperature and high filtration velocity systems.

Wet Scrubbers

High energy wet scrubbers (venturi) are capable of fine particulate control on some sources. Research on these devices should be directed to:

1. Optimization of condensation effects which may occur in venturi scrubbers; and

2. Development of new nozzle configurations which can both accelerate and shear the water stream into small drops at lower energy expenditures.

EMERGING CONTROL SYSTEMS

The Steam-Hydro Air and ADTEC scrubber systems both offer promise as new systems for the control of fine particulate emissions in the near future. Both of these systems appear applicable to a wide range of sources, and additional demonstration testing is recommended.

PROPOSED CONTROL SYSTEMS

Condensation scrubbers, charged droplet systems, electrified filters of various types, and foam scrubbers have sufficient potential for collecting fine particles to merit additional research and development. Future studies on any of these systems should be conducted in equipment configurations and sizes that will produce reliable engineering design data. Recommendations for each system are outlined next.

Condensation Scrubbers

The work on condensation scrubbing which has been conducted to date indicates it can be an important avenue to exploit in order to collect fine particulates. Previous work has shown that the specific details of heat and mass transfer, the initiation of condensation, and various particle properties have very significant influence on condensation scrubbing. Current knowledge of the interaction of key parameters is minimal--especially in equipment configurations that are likely to be useful in actual industrial gas cleaning applications. Additional R&D is recommended to develop requisite data.

Multiple-stage or continuous-type equipment is superior to single-stage equipment for both the steam injection or sudden cooling approaches to condensation scrubbers, and multiple-stage equipment is recommended in future studies. In the steam injection mode, research should be conducted to determine:

1. Optimum steam requirements on each stage;

2. Interstage cooling requirements; and

3. Performance of multistage equipment with a variety of particulates representative of industrial emissions.

Research on sudden cooling should focus on determining the results of the addition of low-grade steam to hot gas streams followed by controlled cooling. Specific factors that should be defined are:

1. Necessary thermodynamic conditions; and

2. Optimum equipment configurations.

Charged Droplet Systems

Currently available data on charged droplet scrubbers and related devices indicate some potential for the collection of fine particles. However, theoretical models generally predict poorer performance than has been observed in the limited experimental work conducted to date. Additional work on the theoretical aspects of charged droplet scrubbing and on bench- or pilot-scale equipment is recommended. Emphasis should be placed on experimental work on bench-scale or pilot-scale equipment so that meaningful engineering design data are obtained.

Electrified Filters

Limited theoretical and experimental studies on idealized systems indicate that electric fields do improve the collection efficiency of various filter systems (e.g., fabric filters, wire mesh filters, granular beds, fluid beds). It is not clear whether electrified filters will be adaptable to the control of emissions from industrial processes.

Research to explore the feasibility of this class of device in more detail is recommended. The initial stage of the research should be a detailed evaluation of the advantages and disadvantages of the various types of electrified filters and the selection of the most viable for additional evaluation. Experimental evaluation under actual field conditions is strongly recommended.

Foam Scrubbers

The addition of a surface-active agent to wet scrubbers has been reported to increase the collection efficiency. At present, the mechanisms of foam scrubbing are ill-defined and the utility of foam scrubbing for particulate collection is difficult to determine.

Because the information on the mechanics of foam scrubbing is meager, research on all aspects of the process (i.e., foam generation, bubble flow and dynamics, heat and mass transfer and bubble destruction) is recommended.

INTRODUCTION

As man has become more knowledgeable about the impact of particulate pollutants, he has become increasingly aware of the importance to his well being of the action of fine particles. While our present understanding of the interaction between man and fine particulates does not permit a quantitative assessment of the overall influence of fine particulates, information continues to accumulate which points to many negative features of fine particulate pollutants.

Control of the atmospheric loading of fine particulates poses a challenge because both primary fine particulates and secondary fine particulates (formed by complex transport and reaction processes in the atmosphere) contribute to the overall atmospheric loading. It is likely that in order to insure the control of atmospheric fine particles which exhibit adverse human health and welfare effects, control technology will ultimately be needed to control both primary fine particulates and the gaseous precursors of secondary fine particulates.

Midwest Research Institute (MRI), under a grant from the Air Pollution Control Division, Office of Research and Development, Environmental Protection Agency undertook a study to assess the state of the art of control technology for fine particulates* emitted from stationary sources. Emphasis was placed on the analysis of control technology for primary particulates.

The initial activity in the program was directed to a general review of collection and agglomeration mechanisms for particulates. Both theoretical and experimental facets were reviewed with attention focused on forces or collection mechanisms expected to be of importance for fine particles. The results of the review provided necessary background information and input for the subsequent analysis of control technology.

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* There is no universally accepted definition of fine particulates, and in this study, we have chosen an upper cut-off point of 3 microns diameter.

The analysis of control technology for fine particulates was centered on: (1) conventional control equipment; (2) emerging control technology; and (3) proposed or conceptual control systems.

The following sections of this report include: (1) a discussion of the highlights of our review of collection and agglomeration mechanisms for particulates; (2) a delineation of promising mechanisms for fine particulate collection or agglomeration; (3) the results of the assessment of conventional, emerging and proposed control technology for fine particulates; and (4) a series of appendices.

COLLECTION AND AGGLOMERATION MECHANISMS FOR PARTICULATES

Particulate collection is effected by passing the gas stream through a system where the particles are acted on by forces which remove them from the gas stream. The forces acting give the particles a component of velocity in a direction other than that of the gas stream. To be effective, these forces must be sufficiently large to take the particle out of the gas stream during its residence time in the system. If the particulates in the gas stream are submicron in size, their removal may be facilitated by making agglomerates of the very small particulates and then collecting the agglomerates.

The basic mechanisms or forces that can be used to collect or agglomerate particulates are shown in Table 2. The effectiveness of the individual mechanisms is strongly dependent upon factors such as particle size, flow velocity, particle density, particle number density, temperature gradients, concentration gradients, and heat and mass transfer coefficients. Individual collection or agglomeration mechanisms are briefly reviewed next.

PARTICLE COLLECTION

Many of the forces or mechanisms in Table 2 are not effective in the fine particle size range or do not produce a sufficiently large migration velocity to result in particle separation for realistic residence times. Appendix A presents an analysis of the effectiveness of the individual mechanisms or forces for the collection of fine particles. The main observations are presented in the following subsections.

Gravity and Momentum Forces

Although in theory a very large settling chamber would give sufficient time for even small particles to be collected, practical size limitations restrict the applicability of these chambers to large particles. The efficiency of a simple settling chamber can be improved by giving particles a downward momentum in addition to the gravity settling effect.

Table 2. PARTICLE COLLECTION OR AGGLOMERATION FORCES (MECHANISMS)

- I. Particle collection
  - A. Gravity and momentum forces
  - B. Centrifugal forces
  - C. Aerodynamic capture
    - 1. Inertial impaction
    - 2. Interception
    - 3. Diffusion
    - 4. Electrostatic attraction
    - 5. Gravitational settling
  - D. Flux forces
    - 1. Electrostatic forces
    - 2. Thermal forces
    - 3. Diffusion forces
    - 4. Magnetic forces
- II. Agglomeration and/or particle growth
  - A. Thermal or Brownian agglomeration
  - B. Turbulent agglomeration
  - C. Electrostatic agglomeration
  - D. Sonic agglomeration
  - E. Condensation

The number of possible designs incorporating this principle is very great, varying from a simple baffle in the chamber to specially designed jets which give accelerated settling. While momentum separators do improve collection efficiency, they do not significantly enhance the collection of fine particles.

Centrifugal Forces

Particle removal from spinning gases by centrifugal forces is the method by which cyclones collect particulates. Theoretical and experimental studies have shown that cyclone performance deteriorates rapidly as particle size decreases below 5 microns. The only use of cyclones in regard to the control of fine particles might be as precleaners or in connection with particle agglomeration devices.

Aerodynamic Capture

Aerodynamic capture of particles involves the collection of particles by collecting bodies (e.g., droplets, fibers, packing, etc.). To utilize aerodynamic capture, the gas stream is brought near the collecting bodies and then a number of short-range mechanisms accomplish the actual collection.

In order to achieve a single particle target efficiency* of 90% or greater for particles in the fine particle size range by inertial impaction, velocity differentials in the range of 10^2-10^4 m/sec (3.3×10^2-3.3×10^4 ft/sec) and collecting bodies of 50 microns diameter or less are required (see Appendix A). To achieve the equivalent efficiency by interception, the diameter of the collecting body must be nearly the same as the particles to be collected. For micron and submicron particles, this would mean that the collecting body would have to be about 1 micron in size--a virtual impossibility in practical situations.

Collection of small particles by Brownian diffusion is effective if sufficient residence time is available. If the collection of fine particles by diffusion is to be a significant factor, the Peclet number ($v_g D_c / D_{DM}$) cannot be much greater than 10. In most practical situations, particle collection by Brownian diffusion will be important only for particles less than 0.5 micron in diameter.

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* Single particle target efficiency is defined as

$$\eta = \frac{\text{cross-sectional area of fluid stream from which particles are removed}}{\text{cross-sectional area of filter element projected in direction of flow}}$$

Electrostatic forces between particles and collecting bodies can enhance the collection of fine particles. If the charge on the particles is relatively large, electrostatic forces can be many times greater than mass forces. Comparisons of the target efficiencies for electrical forces with target efficiencies for inertial impaction and diffusion show that for low gas velocities electrical collection may be much greater. Electrostatic forces are likely to contribute significantly to aerodynamic capture of particles in the 0.01-5 micron diameter size range when the gas velocity is low and the charge on the particles is relatively large.

Flux Forces

Particles can be collected by forces which result from electrical, temperature, and concentration gradients, from the flux of matter or energy, and from a magnetic field. This group of forces, often termed flux forces, are attractive for the collection of fine particles, because the magnitude of the flux forces do not approach zero as the size of the particles to be collected approaches the submicron range. Theoretical analysis indicates that, in general, the particle deposition velocity resulting from flux forces should be of the order of 0.1 cm/sec (0.04 in/sec) or larger for apprecialbe collection efficiency in practical equipment configurations. Individual flux forces are discussed in the following subsections.

Electrical Forces - If charged particles are subjected to an unidirectional electric field, they move towards the electrodes and are deposited. In the absence of turbulence or other aerodynamic effects, the migration velocity ω resulting from the electrostatic force can be obtained from Stokes' law and is given by

$$\omega = \frac{qE}{6\pi r_p \mu} , \qquad (1)$$

where q is the charge on the particle, E is the strength of the electrostatic field, r_p is the particle radius and μ is the viscosity of the gas. This expression neglects second-order electrostatic effects such as the polarizability of the particle and assumes that a spherical particle is moving in laminar flow ($N_{Re} < 1$). It is clear from Eq. (1) that for a given particle size the only practical variables affecting the migration velocity are the electric field strength and the charge on the particle.

Some fairly refined theories for particle charging mechanisms have been developed, and these theories and available experimental evidence show a minimum in the charging rate for particles in the 0.1-0.5 micron size range. However, the calculated particle-migration velocities for particles in this size range, obtained by assuming reasonable fields, charge densities and residence times, are nevertheless quite large--of the order of 1 cm/sec (0.4 in/sec). The utilization of electrostatic forces to collect fine particles is a promising avenue to pursue.

Thermal Forces (Thermophoresis) - Particles can be removed from a gas stream by the use of a temperature gradient. The force which causes particle motion results from momentum differences imparted to the particle on opposite sides. The hotter (and thus faster) molecules colliding with the particle will impart a higher momentum to the particle than the cooler (slower) molecules. Aerosol particles will then drift in the thermal gradient toward the cold surface. The motion of aerosol particles associated with a temperature gradient is called thermophoresis.

A number of equations have been developed to calculate the velocity of a particle due to the thermophoretic force. All these equations can be expressed in one general form

$$v_T = -K\left(\frac{\mu}{\rho_g T}\right)\Delta T \quad , \qquad (2)$$

and differ in the definition of K . The factor K allows for the effects of the thermal conductivities of the particle and gas and includes various accommodation coefficients which are not readily measured or evaluated a priori. In simple theories K is independent of particle size, while in the more complicated theories K also depends on particle size.

The thermophoretic velocity is quite low, being of the order of 0.05-0.1 cm/sec (0.02-0.04 in/sec) even at temperature gradients of 10^3°C/cm. Long residence times would be required to achieve significant particle collection at more reasonable temperature gradients. The large space requirements coupled with the high cost of maintaining the required temperature gradient severely restricts applications of thermal precipitators. However, thermal forces might be exploited to enhance the performance of certain types of control devices such as packed or granular beds.

Diffusion Forces (Diffusiophoresis) - In a concentration gradient, which is accompanied by diffusion but not necessarily by net motion of the gas phase, the heavier molecules will impart a higher momentum than the lighter molecules. If there is a net motion of the gas phase (Stefan flow), additional force is applied to the particles. The combination of forces due to Stefan flow and the concentration gradient is referred to as the diffusiophoretic force. Particle movement by this force is called diffusiophoresis.

To exploit the mechanism of diffusiophoresis, the collecting device must be designed such that one component in the gas phase is diffusing toward a collecting surface. The most practical case is the diffusion of water vapor toward a surface. References 1, 2, and 3 indicate that for water vapor diffusing through air at 0°C and 1 atm total pressure, the particle diffusiophoric velocity is given by

$$v_p = -\ 1.9 \times 10^{-4} \frac{dp}{dx} \qquad (3)$$

Theoretical analysis recently completed by Calvert, et al.,[4/] indicates that positive diffusiophoresis (i.e., condensation) can produce particle deposition velocities of 0.1 cm/sec (0.04 in/sec) or larger under the heat and mass transfer conditions of a realistic scrubber.

Magnetic Forces - A force (Lorentz force) is generated when an electrical charge or an electrically charged particle moves in a magnetic field transverse to the field lines. If a dust particle carrying "n" elementary charges "q" moves with a speed v , the direction of the force will be at right angles to both the direction of the field and the direction of motion of the particle so that the particle will be diverted from its original path. As a result of the change in direction of the particle, the possibility of particle precipitation exists.

Equation 4 presents an expression for the terminal drift velocity of a charged particle in a magnetic field

$$v_m = \frac{CnqvB}{3\pi\mu D_p} \quad . \qquad (4)$$

Equation 4 indicates that the terminal drift velocity varies directly with the number of charges on a particle, the particle velocity, and the magnetic field strength, and inversely with the particle diameter. Examination of Eq. (4) indicates that the terminal drift velocity is less than 0.01 cm/sec (0.004 in/sec) for particles 0.1-1.0 microns in size except at very high particle velocities and magnetic field strengths. The above theoretical considerations demonstrate that for all practical purposes the force generated by a charged particle moving in a magnetic field is too small for use in particle separation for industrial gas cleaning.

PARTICLE AGGLOMERATION AND GROWTH

The agglomeration or growth of fine particulates to particles of 2-5 microns in size, as a step in the control of fine particulates, is in principle attractive. If large particles can be produced for reasonable energy expenditures, it would be possible to utilize devices which cause particle agglomeration or growth in conjunction with conventional control systems. Several possibilities exist for particle agglomeration, and condensation of water vapor on particles is the most feasible way to achieve particle growth without agglomeration. The utility of agglomeration and condensation processes are discussed in the following subsections.

Thermal Agglomeration

When the movement of particles leading to contact and agglomeration can be accomplished only by Brownian diffusion, the process is called thermal agglomeration. Thermal agglomeration has a very serious disadvantage with regard to particulate collection--the long time required to achieve significant particle growth. The only variables which can be used to control particle-particle collision rate are gas temperature, gas composition, and the particle concentration. Gas temperature and gas composition are not very useful variables.

One could conceivably change the particle distribution and concentration by seeding the particle suspension with large particles to act as agglomeration sites, but this is not very useful because the total agglomeration rate depends inversely on the square of the particle number density. Thus, thermal agglomeration is not a viable approach to particle growth for the purposes of control of fine particulates.

Turbulent Agglomeration

Turbulence increases the relative velocities among particulates which in turn increases the chance of particle collision. Theoretical studies and limited experimental investigation have shown that the rate of dissipation of turbulent energy per gram of medium must be quite high for the agglomeration rate of micron and submicron particles to be accelerated noticeably above thermal agglomeration rates.

Theoretical studies and available experimental data indicate that turbulence does not significantly enhance the agglomeration constants for particles less than 0.2 micron in diameter, but can increase the agglomeration constant of 0.5 micron particles by about a factor of 10 and 1 micron particles by a factor of 10^2. The power expended to accomplish this increase would be of the order of $10^7 \frac{\text{dyne-cm-sec}^{-1}}{\text{gram}}$ ($\sim$ 40 hp/1,000 ft^3). This is a very high energy consumption rate and, therefore, turbulent agglomeration does not appear attractive if an external source is needed to provide the turbulence. If a stream is naturally highly turbulent, attempts to foster turbulent agglomeration might have some merit depending upon the control system used to collect particles after the agglomeration step.

Sonic Agglomeration

A potentially effective way of agglomerating fine particles is to pass the aerosol through a sonic field. Several different effects are responsible for enhanced particle agglomeration due to sonic forces, including: (1) collection of particles at the antinodes in the sonic standing wave (radiation pressure); (2) hydrodynamic forces between the particles; and (3) additional collisions due to the different vibrational amplitudes of different sized particles. Although no comprehensive theory is available for sonic agglomeration, some idea of the parametric dependence can be discerned from equations which depict each separate mechanism (see Appendix A).

All three forces show a strong dependence on the radii of the particles, with the force due to radiation pressure and hydrodynamics increasing with particle size and the relative vibrational amplitudes decreasing with increasing particle size. There is also a strong frequency dependence for all three forces. At low frequencies all forces are negligible, while at high frequencies the vibrational amplitude of the particles become negligible. There is, therefore, an optimum frequency for acoustic agglomeration which varies with particle size.

There is a rather large body of diverse experimental data on sonic agglomeration. Reference 5 presents an extensive review of both experimental data and industrial experience. Several generalizations can be made from this body of literature.

1. Sonic fields can effectively induce agglomeration in all sizes of suspended particles, including those in the submicron range.

2. All materials can be agglomerated.

3. The efficiency of the agglomeration depends upon the square of the particulate concentration. The minimum particulate loading, that can be treated, is usually given as 1.1-2.3 g/m^3 (0.5-1.0 $grains/ft^3$), although number density and mean size would appear to be more important parameters. For more disperse particulate suspensions it is necessary to seed the system or to add a mist to bring the particle loading to a satisfactory level. The addition of mist is quite inefficient because some of the mist added will also agglomerate and disappear from the system before particle agglomeration is achieved.

4. The sonic agglomeration process is strongly frequency dependent, with the optimum frequency varying with the particle size or sizes to be agglomerated. Optimum frequencies range from a few hundred to an upper limit of about 10,000 Hz.

5. The required residence time for a given degree of agglomeration varies with field intensity, and minimum field intensities of about 140 dB are required for usable residence times. For a 150-160 dB field a residence time of 5 sec is typical.

Agglomeration of Charged Particles

One method of increasing the rate of agglomeration of fine particulates is to add a bipolar charge, either with or without an externally imposed field. If relatively large electrostatic forces between particulates can be produced, a significant increase in the rate of agglomeration of submicron particulates can result.

Fuchs[6/] and Zebel[7/] have shown that the influence of particle charge on agglomeration rates can be expressed in terms of a correction factor, k_{em} to the agglomeration constant in the absence of particle charge, K_o . The correction factor, k_{em} , is a function of the charge on individual particles and the particle size of individual particles. For weakly charged monodisperse aerosols (see Figure A-14, Appendix A), there will be little change in the agglomeration rate for fine particles. For highly charged aerosols, the agglomeration rates can be much higher (up to 10^2-10^3 times that of the uncharged aerosols), but will usually fall rapidly because of annihilation of the charge upon agglomeration and the decrease in number density. This result could be unfavorable because it may not be possible to achieve significant growth of fine particles.

However, if we consider a bipolarly charged polydisperse aerosol containing a significant number of relatively large particulates as well as the fine particulates, the situation appears much more favorable because it may be possible to collect the fine particulates on the large particulates. If the particle charge on an individual particle is proportional to the particle surface area and if the small particles cover the large particle as a coating no more than one layer thick, the number of small particles which can be deposited on the large particle before charge neutralization is of the order of

$$\left(\frac{\text{diameter of large particle}}{\text{diameter of small particle}}\right)^2 \quad .$$

Thus, the neutralization of a large particle will require a substantial number of small particles and the fine particle concentration in a gas could be significantly reduced before charge annihilation. The utilization of a bipolarly charged polydisperse aerosol to effect particle agglomeration is a promising avenue for additional study.

Particle Growth by Condensation

The size of particles can be increased by causing a vapor to condense on the surface. The most practical vapor to utilize for this purpose is water. Nucleation and condensation processes for water have been studied in some detail. Water vapor may self-nucleate and condense into drops in the absence of condensation nuclei if the degree of supersaturation is great enough. At lower supersaturations, however, a nucleating surface is necessary for condensation. The conditions necessary for condensation to occur on a surface are determined by applying equilibrium thermodynamics. If an insoluble surface is present, drops of the critical radius will form on this surface at a higher rate than they will self nucleate. This is due to the fact that they have less volume and require fewer molecules than for the case of homogeneous nucleation; hence the free energy increase is smaller. Their volume is smaller because they can form as a partial sphere resting on the surface rather than the complete sphere necessary in the absence of the surface. If the particle is soluble, nucleation will occur even more readily

After a drop of critical size has been nucleated, it grows at a rate determined by the ambient environment and the conditions at its surface, just as the condensation flux to a flat wall depends on these boundary conditions. Various equations have been developed to describe the rate of growth and, in general, they all require knowledge of the rate of mass transfer, rate of heat transfer, and phase equilibrium.

If particle growth of fine particles due to condensation can be achieved and particles grown to 2-5 microns, subsequent collection of the droplets could be achieved in conventional equipment. Thus, particle growth has the advantage that high particle deposition rates can persist after heat and mass fluxes are dissipated because once the particles are enlarged they can be collected at little additional pressure drop.

SUMMARY

The review of collection and agglomeration mechanisms for particulates pinpointed mechanisms or forces which should be the most useful for the control of fine particulates. Foremost in this regard are inertial impaction, flux forces, electrostatic agglomeration and sonic agglomeration. Some of these mechanisms or forces are already employed in conventional control equipment, but in general in a somewhat inefficient manner. In some instances it may be possible to modify or redesign conventional control systems to enhance the contribution of the promising mechanisms and improve fine particulate removal. Alternatively, new control systems will have to be developed. The following sections of this report discuss: the current capability of conventional control equipment to collect fine particles and avenues to pursue to improve performance of conventional equipment,and the capability of recently developed or proposed systems for the collection of fine particles.

FINE PARTICLE COLLECTION BY CONVENTIONAL CONTROL EQUIPMENT

The status of conventional control equipment was reviewed in order to define the extent of our existing capability in regard to the control of fine particulate emissions. A secondary objective was to identify possible avenues for improving the performance capability of conventional equipment with emphasis on the collection of fine particles.

While conventional control devices do in fact collect fine particulates in some applications, the performance of conventional control equipment is often not satisfactory. The poor performance with regard to fine particulates results from:

1. Inherent limitations of conventional control equipment in the fine particle size range, and

2. Lack of previous need to control fine particulates and the attendant lack of interest in optimizing systems with emphasis on the collection of fine particles.

Item 1 results from the fact that the mechanisms or forces exploited in a specific device are not effective in the fine particle size range. The second item, which is only applicable to control systems not inherently limited by the forces or collection mechanisms utilized in the systems, is a result of previous priorities established for the collection of particulate emissions.

Exceptions to the preceding comments exist where conventional collection systems have reached very high mass efficiencies resulting in significant capture of fine particulates along with large particulates. Installations of high efficiency electrostatic precipitators, fabric filters, and high energy wet scrubbers have been reported which achieve relatively high collection of fine particulates.11,33-34/ It would appear that at least some combinations of conventional control systems and source characteristics can result in significant control of fine particulate emissions.

The analysis of conventional control equipment performed in this study was focused on systems deemed capable of significant collection of fine particulates, i.e., electrostatic precipitators, fabric filters, and high efficiency wet scrubbers. The principal findings of the review are highlighted in the following sections.

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators utilize the migration of charged particles in an electric field for the collection of particulates. In the absence of turbulence or other aerodynamic effects, the migration velocity ω resulting from the electrostatic force is given by Eq. (1), p. 19.

The potential usefulness of a "conventional" electrostatic precipitator for the control of submicron particulates can be semi-quantitatively assessed in terms of the migration velocities and the Deutsch equation[8]

$$f = 1 - e^{-A\omega/V} , \qquad (5)$$

where f is the fractional efficiency for a particle with a migration velocity ω of a precipitator with a collecting surface with an area A and a gas volume flow rate V. Although the Deutsch equation is not rigorous, it is acceptable for the purposes of this discussion.

Modern high efficiency electrostatic precipitators are often designed with 1.3-2.0 m^2 of collection area per cubic meter per minute of gas flow (400-600 ft^2/1,000 cfm),* and operate with fields in excess of 10^5 v/m and charge densities of 2-5 x 10^{13} ions/m^3. Particle migration velocities of the order of 2 cm/sec for 0.2 micron diameter particles and 3 cm/sec (1.2 in/sec) for 1 micron diameter particles can be estimated under these conditions (see Figure A-6, Appendix A). Fractional efficiences calculated from Eq. (5) using these migration velocities and A/V ratios are shown in Table 3.

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* Electrostatic precipitators currently designed with 400-600 ft^2/1,000 cfm are typically for flyashes having high resistivities.

Table 3. ESTIMATED FRACTIONAL EFFICIENCIES OF ELECTROSTATIC PRECIPITATOR[a]

A/V		D_p	ω		Fractional Efficiency (%)
(min/m)	(min/ft)	(micron)	(cm/sec)	(in/sec)	
1.48	0.45	0.2	2	0.79	83
1.64	0.50				86
1.80	0.55				89
1.97	0.60				90
1.48	0.45	1.0	3	1.18	93
1.64	0.50				95
1.80	0.55				96
1.97	0.60				97

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[a] Electric field - 2×10^5 v/m.
Charge density - $2\text{-}5 \times 10^{13}$ ions/m^3.

The general validity of these very crude calculations is suppored by recent field testing of high-efficiency electrostatic precipitators with advanced particle sizing techniques. The data shown in Figure 1, obtained by Southern Research Institute, illustrate this point. Figure 1 presents measured and computed efficiency as a function of particle size for a 99.6% overall efficiency ESP operating on a coal-fired power plant. Cascade impactors and a diffusion battery were used to obtain the fractional efficiency data. Collection efficiencies in excess of 90% on a mass basis were noted for particles in the 0.1-1.0 μm size range. On a number basis, the electrostatic precipitator is removing 95% of the particles.9/

Similar fractional efficiency characteristics for electrostatic precipitators have been reported by European investigators. Figure 2 presents some data reported in Ref. 10. Neither the type of source being controlled nor the sampling procedures used to obtain the fractional efficiency data were reported in Ref. 10.

Unfortunately, the electrical characteristics of particulates emitted from many specific sources fall outside the range where capture by electrostatic precipitation is most effective. Modifications to the designs of electrostatic precipitators or conditioning of the particulate emissions (or both) could be necessary to capture fine particulates in those cases.

The important point which emerges from the preceding calculations and comparison with recent field testing is that combined increases in the size of electrostatic precipitators, the charge density, and the field strength can produce collection efficiencies of 90% or greater for fine particulates. These changes are within the present state of the art and should be economically feasible. Furthermore, it appears possible that equivalent effects can be obtained by using precipitators with multiple stages and/or increased sectionalization. Conditioning of the particulates might also be used to enhance collection efficiency.

Consideration should also be given to the further development of wet electrostatic precipitators. Exit grain loadings as low as 0.002 g/m^3 $\left(0.001 \frac{\text{grains}}{\text{ft}^3}\right)$ and overall collection efficiencies of 99.9% have been reported for wet electrostatic precipitators.35/ Although not verified by careful testing, high efficiency for submicron particulates is also claimed at low power consumption. Water usage rates are reported to

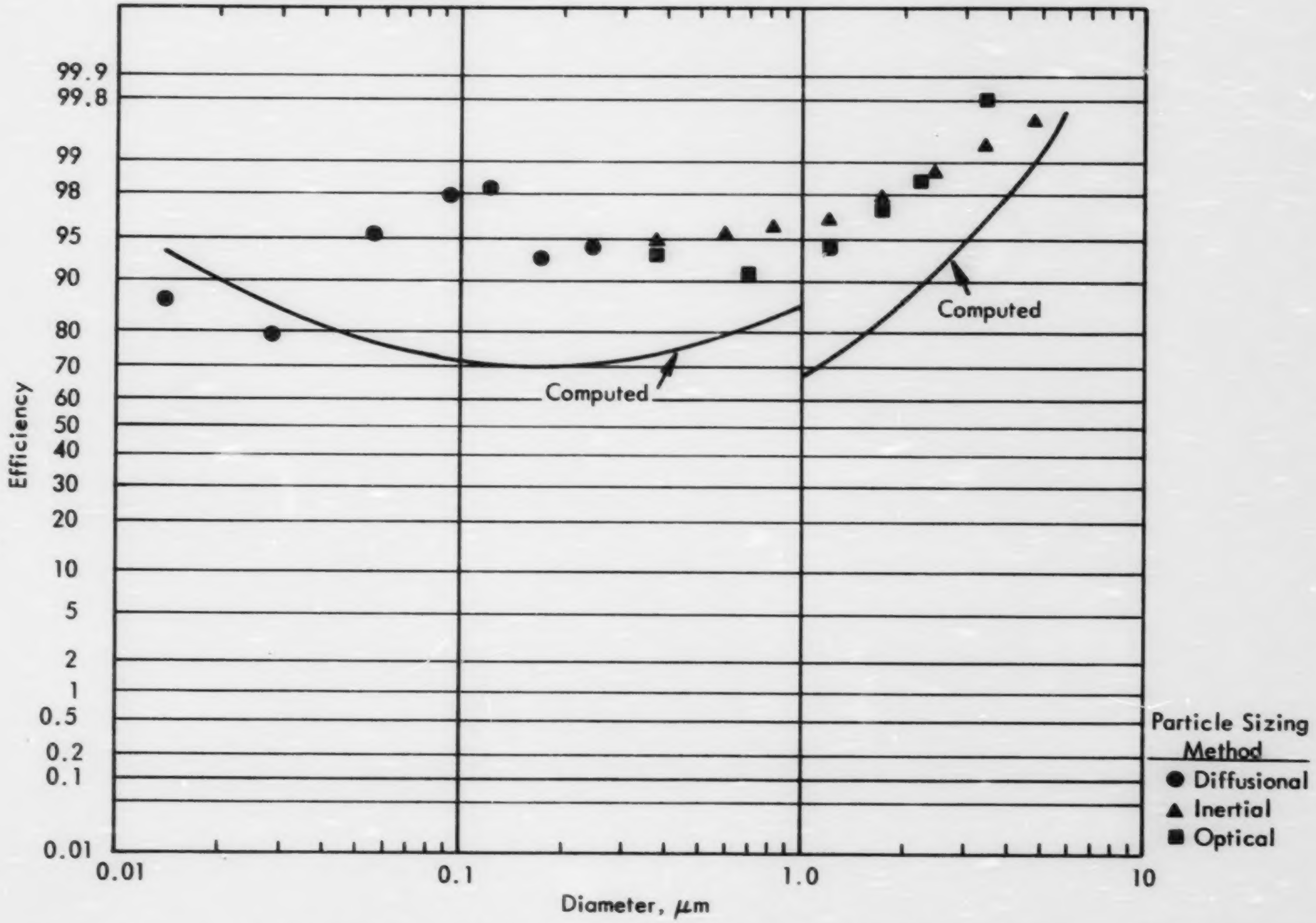

Figure 1. Measured and computed efficiency as a function of particle size for electrostatic precipitator installation at a coal-fired power plant[9]

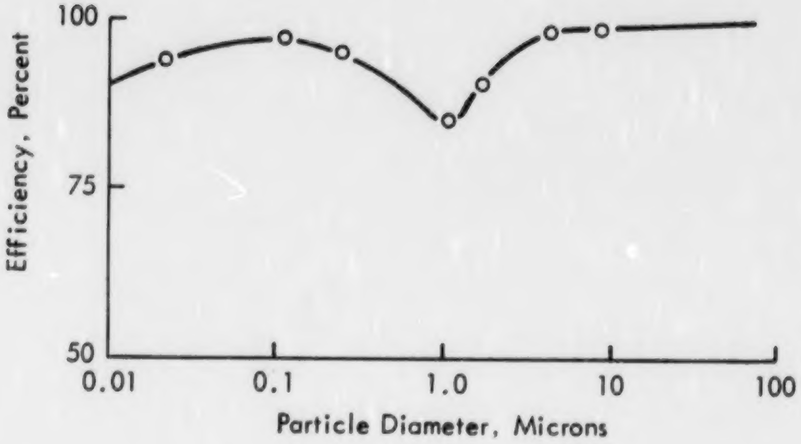

Figure 2. Variation of electrostatic precipitator efficiency with size of particle dust (sizing by electron microscope)[10]

range from 0.07-1.3 liters/m^3/min (0.5-10 gal/1,000 cfm) of recirculating water, depending upon equipment configurations. Pressure drops ranging from 0.2-2.5 cm H_2O in the electrostatic section have been reported.

One of the most important advantages of wet systems in comparison to dry units is the efficient collection of a wide range of dusts. Since the particles are generally thoroughly wetted in this type of precipitator, they are preconditioned and are effectively charged and precipitated, regardless of the degree of resistivity of the material. Particle reentrainment would also be essentially zero in these systems. Wet electrostatic precipitators also generally operate at gas velocities of higher magnitude than those in conventional dry precipitators. For this reason, the device is much smaller, more compact, and requires less installation space than does conventional equipment, thereby reducing the capital cost. The major disadvantages of wet electrostatic precipitators are the need to handle a wastewater stream and a possible increase in equipment corrosion.

FABRIC FILTERS

On those sources where they can be used, fabric filters are excellent control devices for fine particles. Our review of the theoretical models of fabric filtration led to the conclusion that existing models are of limited use in assessing possible avenues for improving fine particle collection by fabric filters. The relatively limited utility of existing models arises from the fact that the models are usually based on single fibers or incorporate the assumption that the filters are sufficiently clean for no deposition to take place on previously deposited particles. The latter assumption is the most serious limitation with regard to industrial fabric filter systems.

A layer of deposited particles, called the filter cake, forms part of the filtering media in an industrial fabric filter. While the deposit is building up and the filter is becoming clogged, through use, important changes may take place which considerably alter its filtering characteristics. There appear to be two main factors. First, the distribution of pore size may be wide so that flow takes place preferentially through coarse pores and the filtration efficiency is low. When the coarse pores become clogged, to a certain extent, the pore distribution becomes more uniform and the median pore size is smaller so that both flow resistance and collection efficiency rise quickly.

Secondly, the deposited particles do not as a rule distribute themselves evenly over the surface of the fibers, but build up chain aggregates which act themselves as very fine fibers and may collect particles more effectively than the material of which the filter is made. Available information indicates that particles which choke a filter most rapidly have acicular shape, and that small particles act more effectively than large ones.

Our review has demonstrated clearly that the performance of fabric filter systems are dependent upon the interaction between particle properties and the engineering parameters of the filter system. The important properties of the particulate matter include the diameter, size distribution, shape, surface characteristics, electrostatics, chemical reactivity, adhesiveness and hydroscopicity of the particles. They affect the structure of the deposited cake; its flow resistance; the power required for filtration; the rates of plugging and blinding; and the rate of mechanical abrasion of the fabric. In addition, they influence the particulate penetration through the filter, and thus, affect the collection efficiency of the systems.

The air-to-cloth ratio, cleaning mechanism, temperature, humidity, weave pattern, fabric weight, fiber diameter, gas flow rate and filter fabric "surface" characteristics appear to be the most important engineering parameters. The filter fabric "surface" is defined as that region of the fabric which, in successive loading and cleaning cycles, has a significant influence on deposition and removal characteristics. Little appears to be known about the electrical, geometric, adhesive and mechanical properties of the filter fabric "surface" despite the fact that the interface between the dust and fabric "surface" is, perhaps, the most important facet of the entire fabric filter system. A conclusion of the analysis of fabric filtration is that improved collection of fine particulates might well result from a better understanding of the interface between particulate properties and the characteristics of the filter fabric "surface."

A potential negative feature that may result from improved collection of fine particles would be an increased difficulty of cleaning fabric filters with an attendant increase in pressure drop during normal operating cycles. Currently, fabric filters on industrial installations typically operate with a pressure drop of about 10.2 cm wg. (4 in. wg.). The maximum pressure drop for effective operation has not been defined, and with modifications to fabric filters high pressure drop systems may be feasible.

Fabric filter systems currently available have inherent limitations which preclude their use on a variety of sources of particulate pollutants. In general, fabric filters require a rather low linear gas velocity for effective operation. Also, most filter media must be used at relatively low temperatures and on a relatively dry gas in order to function properly and avoid excessive deterioration. Many also have rather limited resistance to corrosion and rather low mechanical strength, which limits the amount of handling they can withstand. Research and development work to extend the range of source applications of fabric filters should be given consideration, especially the development of high temperature and high filtration velocity systems.

WET SCRUBBERS

The collection of particulates by wet scrubbers results from a variety of interactions between the gas and liquid phases. Wet scrubbers cover a wide range of designs, sizes, and performance capability. No single mathematical model has been developed which will adequately predict the operating characteristics or efficiency for this broad class of collectors. In the past, even for a single type of scrubber the design equations have not been too accurate and are generally empirical in nature.

Recently Calvert, et al.,[11/] have used the following categories to describe the various types of scrubbers: plate, massive packing, fibrous packing, preformed spray, gas atomized spray, centrifugal, baffle, impingement and entrainment, mechanically aided moving bed, and combination. Calvert has used an approach to understanding and designing scrubbers--the unit mechanism--that is extremely useful in trying to predict ways in which scrubber efficiency can be improved for collection of micron and submicron particulates.

Examples of unit mechanisms include:

Scrubber Type	Unit Mechanisms
Venturi	Liquid jets, sheets, and drops
Sieve plate	Gas jets and bubbles
Impingement plate	Gas jets, jet impingement, liquid drops and sheets
Mobile packing	Gas jets, liquid jets, drops and sheets
Packed column	Liquid sheets and drops, curved liquid sheets, gas jets, and bubbles

To determine the scrubber collection efficiency using the unit mechanism approach requires consideration of transport phenomena such as diffusion (molecular and turbulent), inertial impaction, interception, electrostatic attraction, diffusiophoresis, thermophoresis, etc. The effectiveness of a given scrubber in collecting submicron particulates can be estimated from the unit mechanisms and the transport phenomena involved.

High energy wet scrubbers (i.e., venturi and disintegrator types) are capable of fine particulate control. The high energy scrubbers utilize inertial impaction as the principal collection mechanism. The effectiveness of inertial impaction as a collection mechanism decreases markedly at particle sizes below 1 micron unless high velocity differentials are maintained between the collecting bodies and the particles. The contribution of inertial impaction could also be enhanced by decreasing the size of the collecting bodies. In order to maintain or increase velocity differentials and decrease the size of the collecting bodies (water drops), energy consumption will have to be increased. Thus, while there may be some possibility for improving fine particle collection by conventional venturi type scrubbers, even higher energy consumption is likely.

Improvement in collection efficiency for fine particles of other types of conventional wet scrubbers will come from designs that take better advantage of flux forces--thermophoresis, diffusiophoresis, etc.

SUMMARY

Well-designed conventional control systems (i.e., systems optimized with respect to the collection of fine particulates) are capable of achieving relatively high collection of fine particulates.

High-efficiency electrostatic precipitators appear to offer considerable potential in this regard. Changes within the present state of the art (i.e., increases in the A/V ratio, charge density, and field strength) could produce significant improvement in the collection of fine particulates by electrostatic precipitators.

Improvements in fabric filter technology might also result in better control of fine particles from some sources. Avenues to pursue to improve performance are not as clear-cut as with electrostatic precipitators. Improvements in fabric filters which would permit their use on a wider spectrum of emission sources would be an important advance.

New designs for high-energy wet scrubbers which produce smaller water droplets and higher differential velocities at energy expenditures equivalent to or lower than currently available systems would be an avenue to pursue.

EMERGING AND PROPOSED CONTROL SYSTEMS FOR FINE PARTICULATES

A variety of devices, touted as being effective for the collection of fine particulates, have been reported in the literature. The devices range from concepts or proposals to laboratory-scale devices to full-scale units that have been tested on industrial sources of fine particulates. During this study attempts were made to obtain all readily available information on many of these devices in order to evaluate their potential. The technical staff of the Particulate Technology Section, Particulate and Chemical Processes Branch, Control Systems Laboratory (CSL), provided valuable technical information and other data on several of the systems. Research, field testing, and theoretical evaluations have been or are currently being conducted under CSL sponsorship on some devices discussed in this section.

Appendix B discusses some of the emerging systems, while Appendices C-I present evaluations of concepts or proposed systems. Table 4 delineates the systems reviewed in these Appendices and the highlights of the review are discussed next.

EMERGING CONTROL SYSTEMS

The emerging control systems listed in Table 4 are those systems for which sufficient data could be obtained to make an assessment of performance capability. The individual systems are discussed in some detail in Appendix B. Of the systems analyzed, the Steam-Hydro Air Cleaning and the ADTEC Wet Scrubber were judged to have the most immediate potential for use as fine particle control systems. Wetted-knit mesh separators also appear to have potential on some applications. These systems are discussed briefly in the following sections.

Table 4. EMERGING AND PROPOSED CONTROL SYSTEMS FOR FINE PARTICULATES

I. Emerging Control Systems

- A. Steam-Hydro Air Cleaning
- B. ADTEC Wet Scrubber
- C. Cross-Flow Nucleation Scrubber
- D. PENTAPURE™ IMPINGER
- E. Dynactor Wet Scrubber
- F. Mystaire™ Scrubber
- G. Dupont Wet Scrubber

II. Proposed Control Systems

- A. Granular bed filters
- B. Fluidized beds
- C. Condensation scrubbers
- D. Foam scrubbers
- E. Charged droplet scrubbers
- F. Electrified filters
- G. Gamma-ray precipitator
- H. Sonic agglomerators

Steam-Hydro Air Cleaning System

Lone Star Steel has recently developed a wet-scrubbing system which utilizes a high-speed steam drive with injected water to accomplish the removal of particulate pollutants. The system consists of a steam nozzle, water injector, mixing tube, and twin cyclones. (See Figure B-1, Appendix B.) Normally, the system operates on energy produced by waste heat captured from the process being controlled. The heat is used to generate steam in a waste heat boiler. In installations where little or no waste heat is available, supplemental heat may be provided. In many cases, a package steam boiler may supply all the energy.

The steam nozzle, a proprietary design, surrounded by eight spray nozzles (see Figure B-2, Appendix B) is a key element in this system. The exit velocity of the steam is about 1,050 m/sec (3,500 ft/sec). The function of the steam is to break up or shear the surrounding water spray and to provide for moving the gas stream through the system. The flow rate of injected water controls the cleaning efficiency. The steam flow rate has little to do with the cleaning efficiency, but some is required to shear the injected water spray. Particle collection occurs primarily by inertial impaction. Since the velocity of the collecting bodies is about 10^3 m/sec, single target efficiency of 90% or greater would be expected (see Figure A-2, Appendix A).

Steam requirements, as reported by Lone Star Steel, range from 0.03-0.16 kg of steam per cubic meter of gas (2-10 lb/1,000 ft^3), depending primarily on upstream process draft requirements. Water rates are 0.23 kg of H_2O per kilogram of gas (230 lb of H_2O/1,000 lb of gas) for the conditioning or atomizing chamber and for the spray nozzles surrounding the steam jet.

Efficiency tests have recently been performed by a contractor* funded by CSL on units installed on multiple open-hearth (oxygen lanced) steel furnaces at Lone Star Steel. Preliminary test results indicate collection efficiencies of 99.9% or greater. During the tests, inlet grain loadings averaged 2.88 g/m^3 (1.26 grains/scf), but varied from 0.23-6.86 g/m^3 (0.1-3.0 grains/scf) depending on the point in the process cycle. Outlet grain loadings ranged from 0.002-0.02 g/m^3 (0.0008-0.0089 grains/scf). The inlet size distribution of particles had a mass mean diameter of 1.5 microns and nearly all the particulate was less than 3 microns in diameter.9/

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* Tests performed by Southern Research Institute using cascade impactors and a diffusion battery for particle sizing and fractional efficiency measurements.

Capital, operating, and maintenance cost data are not available for the device. Lone Star Steel has stated that "the installed cost is more than competitive with conventional devices (excluding cost of waste heat boilers)."[12]

Based on the results of the preliminary tests, the Steam-Hydro system offers promise as a new system for the control of fine particulate emissions. The system appears to be applicable to a wide range of sources, but primary applications are likely to be sources where waste heat is available and which emit fine particulates. Where waste heat is not sufficient to power the system, supplemental heat may be used. However, the use of supplemental heat would add to the overall cost of the system.

ADTEC Wet Scrubber

The ADTEC system, developed by Aronetics, Inc., Tullahoma, Tennessee, is a wet scrubbing system that operates on the conventional venturi collection-mechanism of inertial impaction, but establishes the requisite particle-droplet differential velocity by utilizing waste process heat rather than external energy.[13] The Aronetics system is shown schematically in Figure B-4, Appendix B. Waste gas from the industrial process passes through the heat exchanger, the two-phase jet, and the separator, in that order. Water is pumped at 300 psi to a heat exchanger where heat is transferred to the water from the gas, increasing the temperature of the water to the required level, usually between 300°F and 400°F. Expanding through the nozzle of the two-phase jet, partial flashing occurs (approximately 15% vaporizes) and the remaining liquid is atomized (water droplets average approximately 10 microns). Thus, a two-phase mixture of steam and small water droplets leaves the nozzle at high velocity. The dirty gas is entrained by this high velocity two-phase mixture, and in the ensuing mixing with the gas, cleaning occurs primarily by impaction. At the same time, transfer of momentum to the gas results in a pressure rise across the mixing section. This pressure rise provides the motive force to move the gas through the system.

The mixture of steam, gas, and entrained water with dust collected in cleaning passes through the separator after discharging from the mixing section. The water with the dust is removed from the gas and steam mixture which then leaves the separator through the stack. The water with dust is discharged from the separator to the wastewater treatment subsystem. Chemicals and other treatment are applied to remove the dust and other contaminants from the water for recovery of the water and to prevent scale and corrosion in the system.

The treated water is returned to the pump for recycling and sludge is removed for disposal by other pumps not shown. Make-up water to replace water leaving the system through the stack in vapor form and with the sludge is introduced in the separator where some heat is transferred to the make-up water from the gas.

Since the transfer of momentum produces a pressure rise across the mixing section which provides the motive force to move the gas through the system, the ADTEC system does not require, nor does it include, a blower which is necessary in other cleaning systems or methods.

A test unit was installed on a ferro-alloy furnace of the Chromium Mining and Smelting Corporation (Chromasco) at Woodstock, Tennessee. Test results from the pilot system are given in Table B-1, Appendix B. Collection efficiencies of 99+% were reported. Since the device is similar in some respects to the Lone Star Steel system, collection efficiencies of the two systems should be comparable. The Control Systems Laboratory is currently planning to fund additional testing of the ADTEC system using the latest techniques for particle sizing and fractional efficiency measurement.

Mechanical energy consumed in pumping the water to the required pressure of 275-300 psi is about 0.1 hp/m^3/min of gas (3 hp/1,000 cfm), while the power required in the form of heat input to the water from the gas stream exceeds 7 hp/m^3/min (200 hp/1,000 cfm). The latter power requirement would obviously be excessive if it were not supplied by waste heat from the gas stream. Capital costs have been estimated by Aronetics to be between those of venturi scrubbers and fabric filters.

On the basis of currently available information, this system also appears to offer significant improvement in the collection of fine particles at modest energy consumption rates where a waste gas is available which contains a sufficient amount of thermal energy to heat the water.

Wetted-Knit Mesh Filters

Scrubbing systems involving a wetted-knit mesh filter have recently been developed and promoted by Heat-Systems--Ultrasonics and Dupont.[14,15] In both systems the gas stream is first sprayed with water and then the gas-liquid mixture is passed through a fiber bed structure having a pore size sufficiently fine and a path length sufficiently long to provide intimate contact of the gas stream containing the particulate solids and mist with the liquid.

Figure 3 and Table 5 present some performance data reported by Dupont for a laboratory-scale system.[15] The characteristics of the bed used to obtain the data were:

1. Bed diameter--10.26 cm (4 in.)

2. Fiber material--304 stainless steel in knitted form

3. Packing density--128 kg/m^3 (8 lb/ft^3)

4. Bed void fraction--0.983

5. Specific surface area 459 m^2/m^3 (140 ft^2/ft^3) for 6-mil fiber diameter and 754 m^2/m^3 (230 ft^2/ft^3)

Talc dust with the following size distribution was used in the tests: 50% $<$ 2.4 microns, 28% $<$ 1 micron, and 14% $<$ 0.5 micron. The test results in Table 5 show quite high collection efficiencies with relatively low pressure drop. Sampling procedures used to obtain the data in Table 5 were not reported, but assuming that valid procedures were utilized, quite high collection efficiencies appear possible with relatively low pressure drop. If the efficiencies reported by Dupont for their laboratory-scale system can be substantiated by testing of pilot-scale or demonstration-scale systems, wetted-knit mesh filters will be an addition to technology for the control of fine particulates.

PROPOSED CONTROL SYSTEMS

Numerous concepts have been advanced for the control of particulates over the years. Investigation of the proposed systems has been random in nature and the potential of the proposed systems is generally an unknown. Several broad categories of proposed systems (see Table 4) were analyzed in this program in order to define their potential for use in controlling fine particulates. Appendices C-I present detailed discussions of the systems evaluated. The principal observations for each category are presented next.

Condensation Scrubbers

Condensation scrubbing involves particle removal from the gas stream via the use of a temperature gradient, a vapor concentration gradient, vapor condensation, or a combination of the three. It is not necessary that all forces act simultaneously, but in most actual cases they do.

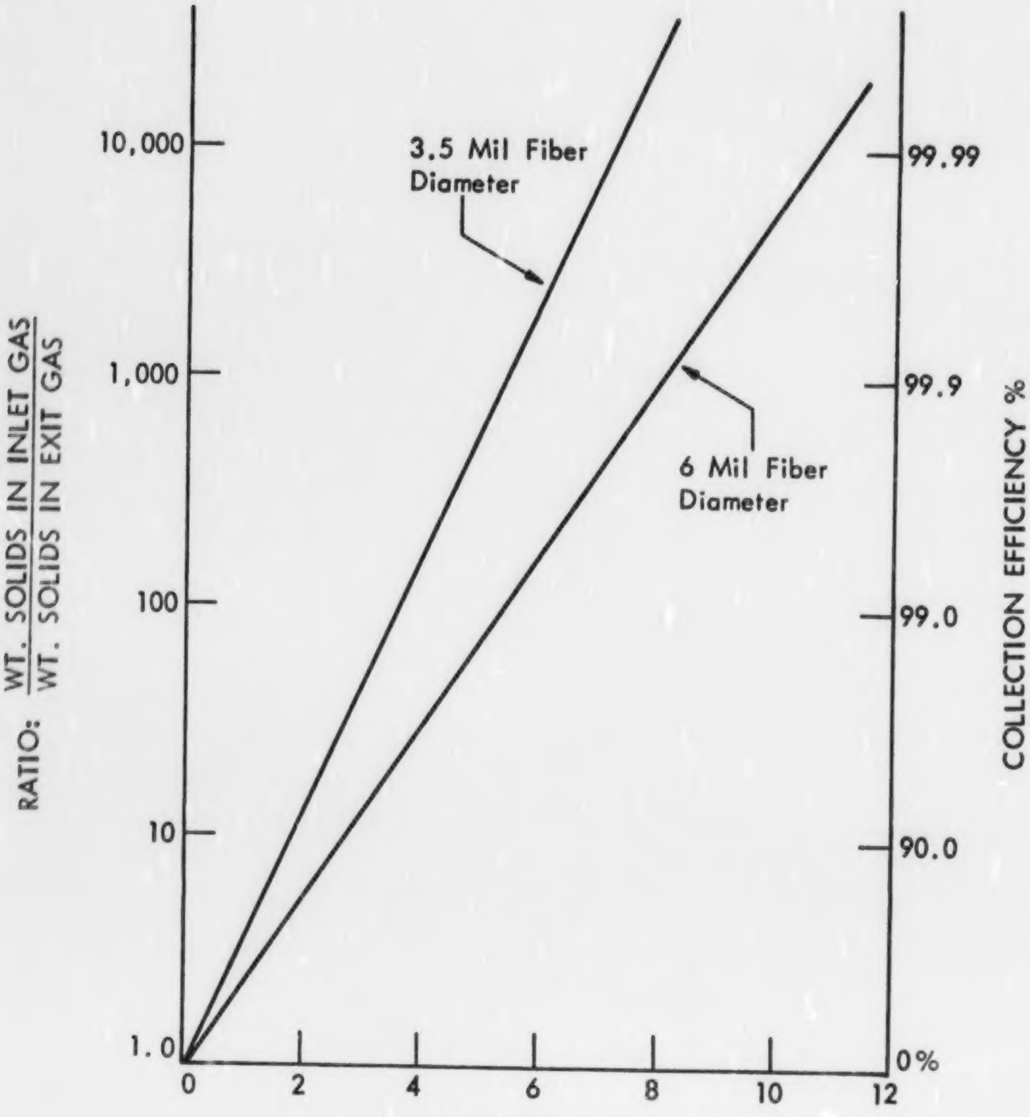

Figure 3. Measured efficiency of Dupont wetted-knit mesh separator collecting 2 micron particles[15]

Table 5. TEST DATA ON DUPONT SCRUBBER

Run No.	Bed Depth (cm)	Bed Depth (in.)	Bed Density (kg/m³)	Bed Density (lb/ft³)	Bed Material	Liquid Spray Rate (liters/min-m² of chamber)	Liquid Spray Rate (gpm/ft² of chamber)	Gas Throughout (m³/min)	Gas Throughout (ft³/min)	Superficial Gas Velocity (m/sec)	Superficial Gas Velocity (ft/sec)	Inlet Dust Concentration (g/m³)	Inlet Dust Concentration (grains/ft³)	Pressure Drop (cm H₂O)	Pressure Drop (in. H₂O)	Collection Efficiency
1	10.2	4	64.1	4	Bed	896	22	5.04	178	10.4	34	30	13	28.7	11.3	98.9
2	10.2	4			composed			5.89	208	12.2	40	32	14	34.8	13.7	98.7
3	10.2	4			of			1.30	46	2.7	9	11	5	7.4	2.9	97.7
4	10.2	4			16 mil			1.84	65	3.7	12	25	11	8.6	3.4	98.4
5	10.2	4			diameter			2.27	80	4.9	16	37	16	11.4	4.5	99.2
6	10.2	4			knitted	977	24	1.36	48	2.7	9	64	28	10.9	4.3	99.8
7	10.2	4			polyethylene			2.66	94	5.5	18	43	19	20.6	8.1	98.8
8	10.2	4						5.04	178	10.1	33	32	14	33.5	13.2	98.9
9	20.3	8						1.36	48	2.7	9	149	65	22.9	9.0	99.4
10	20.3	8						2.61	92	5.5	18	110	48	48.3	19.0	99.6
11	10.2	4	320.4	20	304 stainless steel	407	10	3.71	131	2.7	9	85	37	9.4	3.7	98.8
12	10.2	4			16-mil diameter			5.10	180	3.7	12	[illegible]	37	12.2	4.8	98.5
13	10.2	4	640.7	40	304 stainless	407	10	4.11	145	3.0	10	64	28	24.4	9.6	98.6
14	10.2	4			11-mil			5.01	177	3.7	12	82	36	25.1	9.9	98.9
15	10.2	4	192.2	12	diameter	407	10	3.88	137	2.7	9	50	22	27.2	10.7	99.4
16	10.2	4						4.96	175	3.7	12	62	27	26.2	10.3	98.7

The work on condensation scrubbing conducted to date indicates that the collection of submicron particulates from various gas streams can be enhanced by the use of condensation effects. The collection efficiency is a function of:

1. Amount of water vapor condensed per unit mass of dry gas;

2. Particle concentration with a trend of increasing efficiency with decreasing particle number concentration; and

3. Type of particle being scrubbed (efficiency varies in the order hygroscopic dust > hydrophillic dust > hydrophobic dust).

Our analysis (see Appendix C) of the potential of condensation scrubbing for particulate control indicates that it can be an important avenue to exploit in order to collect fine particulates. Optimization of condensation effects in venturi and orifice type scrubbers could result in decreased power consumption for those classes of conventional wet scrubbers.* Condensation phenomena can also provide the basis for new families of control systems for fine particles.

Two avenues that could be exploited to develop new control systems are: (a) injection of steam into a cold dust-laden gas, and (b) sudden cooling of a hot and humid gas stream. Under proper thermodynamic conditions, injection of steam into a cold dust-laden gas stream can result in the conversion of a portion of the steam into condensed droplets. Water vapor would preferentially condense on the dust and, thereby, increase the effective particle size of particulates, making collection of the particulates easier. Treatment of gas streams by steam injection would not be very effective for gas temperatures above 100-120°F because condensation would not be significant. Sudden cooling is an inefficient method for producing condensation since most of the water will condense on the cooling surface. However, enough condensation will occur on the particles to cause some particle growth.

Multiple stage or continuous-type contact equipment is superior to single-stage equipment for both injection and cooling. Figures C-2 and C-3, Appendix C, present possible equipment configurations. Distribution of condensation over several stages is preferable because of the enhanced growth which can occur after the particle concentration has been reduced.

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* Standord Research Institute is currently conducting research in this area under funding from the Control Systems Laboratory.9/

The economics of condensation will be dependent upon the source and the characteristics of the emitted particulates. Costs for condensation scrubbing will be highly dependent on the amount of steam condensed, especially if steam or fuel to evaporate water must be purchased. Cooling water may also be required to condense the steam and the amount of cooling water needed will depend on the temperature rise of the water in the scrubbing system.

Currently, limited information is available on the details of the phenomena occurring when steam, water droplets, and particulates are mixed--especially in equipment configurations that are likely to be useful in actual industrial gas cleaning applications. In order to resolve the areas of uncertainty and to develop reliable data for engineering design, additional development effort is necessary. Effort should be focused on pilot-scale equipment in order to develop data under realistic heat and mass transfer conditions. The Control Systems Laboratory is currently funding work in this area at A.P.T., Inc., Riverside, California.[9,36]

Charged Droplet Scrubbers

Control devices using charged drops as the collecting bodies are currently under study by several investigators.[16-19] Currently available data on charged droplet scrubbers and related devices indicate some potential for the collection of fine particles. However, adequate data are not now available for a comprehensive analysis of any of the devices. While the ultimate efficiency and usefulness of these devices can not be determined accurately at this time, the major workers in this field estimate from their experience and analysis that efficiencies comparable to, but not much better than, conventional electrostatic precipitators can be obtained for submicron particles.[18,20-21]

Potential advantages of charged droplet systems in comparison to conventional electrostatic precipitators include the ability to clean gases at low voltage levels and elimination of problems of dust reentrainment and of dust resistivity frequently encountered in conventional electrostatic precipitators. Advantages with regard to wet scrubbers include lower water usage and lower pressure drop at the same collection efficiency. Disadvantages in comparison with conventional electrostatic precipitators include:

1. Need to produce and charge drops;

2. Premature space charge precipitation of drops on walls of device;

3. Neutralization of charge of drop upon collection of oppositely charged particulates; and

4. Need to handle wastewater stream.

The main application areas for charged droplet scrubbers are likely to be on sources where conventional electrostatic precipitators or wet scrubbers do not perform satisfactorily. Total energy requirements for charged droplet systems are relatively uncertain, but about 0.07 hp/m^3/min (2 hp/1,000 cfm) appears to be a reasonable estimate.

It is not clear whether the performance of charged droplet systems will be sufficiently greater than alternative control systems to justify their development and subsequent use on industrial gas cleaning applications. Additional research and development activity on charged droplet systems will be required to determine their real merit. Emphasis on future R&D should be placed on experimental work on bench-scale or pilot-scale model systems so that meaningful engineering design data are obtained. Work is currently under way at TRW, Inc., and the University of Washington on charged droplet systems. The former work is being supported by EPA/CSL, while the latter is supported by industry.

Foam Scrubbers

The addition of surface-active agents to water produces a foam and the effectiveness of the collection of particulates by bubbles in wet scrubbers may be increased by the use of foam. At present, the mechanism of foam scrubbing is not well-defined and the utility of foam scrubbing is difficult to determine.

The limited experimental data on foam scrubbers reported in the technical literature indicates good results for aerosol collection by foam.[23-24] Reference 25 describes a foam bed scrubber which is a product of a Swedish firm. Reference 25 reports that the foam scrubber has been tested on a variety of dusts and that collection efficiencies in the 90-97% range are obtained. Information on fractional efficiency of the foam scrubber was not given in Ref. 25.

Based on the limited available information, the potential of foam scrubbers to control fine particles would seem to be good if the residence time is sufficient to collect fine particles. Potential problems in foam scrubbers are formation of fine bubbles for good collection, foam destruction and secondary foaming. More detailed information is required regarding the mechanism of bubble formation, splitting, and destruction before the technical and economic feasibility can be determined.

Electrified Filters

One potential technique for obtaining improved particulate control devices is to use electric fields in conjunction with various filter systems. Fabric filters, wire-mesh filters, granular beds, or fluid beds can be used as the underlying filter elements. The magnitude of electrical forces compared to other forces that can be applied to particulates suggests that improvement in aerosol filtration should occur when electric fields are present in conjunction with filter systems.

Limited theoretical and experimental studies on idealized systems indicate that electric fields do improve the collection efficiency of filter systems. However, it is not clear whether the improved performance of these filters is sufficient to justify their use or whether electrical filters will be adaptable to the control of emissions from industrial processes. Research to explore the feasibility of this class of devices in more detail is warranted.

Granular Bed Filters

The ability of porous beds of granular materials such as sand, coke, sintered materials, Raschig rings, or similar materials to remove particles from gas streams has been known for many years. Although granular beds have found practical application in atomic energy facilities and the filtering of small volume gas streams, application to industrial sources of particulates has been limited.

At present, there are no useful models for aerosol filtration in granular beds. Knowledge of the performance of granular beds has been obtained essentially from experimental studies at both the laboratory and pilot-scale level. Experimental investigations of granular beds have been performed on fixed and moving beds and beds augmented by electrostatic and sonic forces. Meager results on pilot-scale granular bed filters operating on industrial sources of particulate pollutants indicate collection efficiencies in the range 85-98%.[26] Reference 27 reports that a 5.1 cm (2 in.) thick electrified granular bed collected 0.6-0.7 micron methylene blue aerosol with an efficiency of 99.5% at a pressure drop of 0.51 cm wg.

Fluidized Beds

Fluidized beds have also been proposed as particulate filtration media. Experimental studies on fluid beds have shown that collection efficiencies of 90-93% can be obtained from single pass fluid beds. Attainment of high efficiencies by staging may be possible even though single stage efficiencies are not high.

Electrostatically augmented fluidized beds have been studied at Harvard University[28] and MIT.[20]* Experimental studies at Harvard University showed collection efficiencies in excess of 90%.

With the possible exception of electrostatically augmented systems, fluid beds do not offer sufficient potential for fine particle control to warrant additional research. In view of other more promising and simpler approaches, the electrostatically augmented system is also of questionable utility.

Gamma-Ray Precipitator

The idea of utilizing ionizing radiation to charge particulate matter so that it can be collected by electric fields in an electrostatic precipitator has been proposed in the patent literature.[29-32] Experimental studies of the gamma-ray precipitator concept have recently been conducted at Penn State University (see Appendix I). The results of limited tests on the emission stream from a small stoker-fed home-type furnace indicated collection efficiencies comparable to those of conventional electrostatic precipitators.

Potential advantages for the gamma-ray precipitator in comparison to conventional electrostatic precipitators are: (1) possible higher ion densities; (2) lower operating costs; and (3) simplified cleaning systems.

The major disadvantages are the radioactive material required and the shielding structures. Both of these disadvantages will greatly limit the use of such a device even if it is proven highly efficient. Utility companies with experience in handling nuclear materials would appear to be the only likely applications for such a device.

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* The work at MIT has been supported by the Control Systems Laboratory.

Sonic Agglomerators

Sonic agglomerators can be an effective way of agglomerating fine particles to a larger size which could be collected by conventional control equipment.

Sonic coagulation of particulates has as its principal advantage its applicability to any aerosol, including those comprised of submicron particles. The principal disadvantage of sonic coagulation is the relatively high energy requirements, which have been reported to range from 0.05-0.7 hp/m^3/min (1.5-19 hp/1,000 cfm). Mednikov[5/] suggested that minimum total energy requirements of 0.16-0.32 hp/m^3/min (4.5-9 hp/1,000 cfm) should be achievable with optimum design. Presumably this energy requirement is based on agglomeration to a sufficient size to be removed by inertial separators. A second major disadvantage is the low efficiency of acoustic coagulators and their inability to handle highly dispersed suspensions.

The energy requirements of a sonic precipitator with an inertial separator or other simple filtering system are relatively high. Water augmentation appears necessary to obtain the removal of a large fraction of the particulates. If 0.02 kg of water per cubic meters per minute is used, one would expect an increase in the power requirements of up to 0.04 hp/m^3/min depending on the device used and the mean droplet size. The minimum energy requirements would then be 0.2-0.35 hp/m^3/min (5.5-10 hp/1,000 cfm)

Alternatively, one should consider hybrid units. For example, sonic agglomeration could be used upstream from a conventional electrostatic precipitator. Since the particulates now need to be agglomerated to only 1-2 microns instead of 10-15 microns with an inertial separator, a reduction in acoustic energy requirements by at least a factor of 5 would be expected. Other hybrid units should also be possible.

SUMMARY

In the category of emerging and proposed control systems for fine particulates, there are several systems that hold promise for transition to commercially viable systems. Foremost in the category of emerging systems are the Steam-Hydro Air Cleaning and the ADTEC wet scrubber systems. Both of these systems look especially attractive for use on sources where sufficient waste heat is available to provide energy requirements. Furnaces used to process various metallurgical materials would appear to be prime sources for application.

Only limited data are available to judge the potential of most of the proposed systems. Assessments must be based predominately on the ability of the underlying collection forces or mechanisms to collect fine particulates. Condensation scrubbers, charged droplet scrubbers, electrified filters of various types, and foam scrubbers have sufficient potential to merit additional research and development. The Control Systems Laboratory is funding research programs in some of these areas at the current time and a more extensive program appears warranted. Since in general only data on laboratory-scale equipment are available for proposed systems, future studies should be conducted in equipment configurations and sizes that will produce reliable engineering design data.

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GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS

a_i = thermal reflection coefficient

A = area of collecting surface

B = magnetic field strength

c_p = specific heat of gas

C = Cunningham correction factor

D = diffusion coefficient

D_c = diameter of collecting body

D_{BM} = particle diffusion coefficient

D_p = particle diameter

d = distance between particles

E = electric field strength

f = frequency of vibration

F = force

g = gravitational constant

h = bed height/bed diameter

k_g = thermal conductivity of the gas

k_p = thermal conductivity of the particle

k = Boltzmann constant

L = length

m_i = mass of molecules of component i

m_p = mass of particle

n_i = number of molecules of component i per unit volume

N_I = inertial impaction parameter

N_O = ion density

N_R = interception parameter

N_{Re} = Reynold's number

N_{Pe} = Peclet number

p_i = partial pressure of component i

p = pressure

P = penetration

q_p = electrostatic charge on particle

q_f = electrostatic charge on collector

r_p = particle radius

r = radius of rotation

R_b = radius of bubble

T = temperature

t = time

v_{p-g} = particle velocity relative to gas

v_{p-c} = particle velocity relative to collector

v_T = thermophoretic velocity (particle)

v_p = diffusiophoretic velocity (particle)

v_m = particle terminal drift velocity in magnetic field

v = particle velocity

v_{tp} = tangential velocity of particle

v_{tg} = tangential velocity of gas

v_b = bubble velocity

v_g = linear gas velocity

V = volume flow rate of gas

W = width of chamber

α = coefficient of absorption

β = volume shape factor

ϵ = rate of dissipation of turbulent energy

ϵ_p = dielectric constant of particle

ϵ_f = dielectric constant of gas

ϵ_o = permittivity of free space

λ = mean free path of gas

λ_s = wavelength of sonic vibration

λ_o = internal scale of turbulence

ξ = particle mobility

η = collection efficiency

δ = kinematic viscosity

β_c = coagulation constant

ρ_p = particle density

ρ_g = density of gas

ω = migration velocity in electric field

μ = gas viscosity

APPENDIX A

COLLECTION AND AGGLOMERATION MECHANISMS FOR FINE PARTICULATES

INTRODUCTION

Particulate collection is effected by passing a gas stream through a system where the particles are acted on by forces which remove them from the gas stream. The forces acting give the particles a component of velocity in a direction other than that of the gas stream. To be effective, these forces must be sufficiently large to take the particle out of the gas stream during its residence time in the system. If the particulates in the gas stream are submicron in size, their removal may be facilitated by making agglomerates of the very small particulates and then collecting the agglomerates.

The basic mechanisms or forces that can be used to collect or agglomerate particulates are shown in Table A-1. The effectiveness of the individual mechanisms is strongly dependent upon factors such as particle size, flow velocity, particle density, particle number density, temperature gradients, concentration gradients, and heat and mass transfer coefficients. As a result, many of the forces or mechanisms in Table A-1 are not effective for the collection of fine particles. The important parametric dependence of each force or collection mechanism is discussed in the following subsections.

PARTICULATE COLLECTION

Gravity and Momentum Forces

In gravity separators, the gas stream is slowed down sufficiently to allow particles to settle out. The diameter of the smallest size particle that is completely settled out is given by Eq. (A-1)

Table A-1. PARTICLE COLLECTION OR AGGLOMERATION FORCES (MECHANISMS)

I. Particle Collection

- A. Gravity and momentum forces
- B. Centrifugal forces
- C. Aerodynamic capture
    - 1. Inertial impaction
    - 2. Interception
    - 3. Diffusion
    - 4. Electrostatic attraction
    - 5. Gravitational settling
- D. Flux forces
    - 1. Electrostatic forces
    - 2. Thermal forces
    - 3. Diffusion forces
    - 4. Magnetic forces

II. Agglomeration and/or Particle Growth

- A. Thermal or Brownian agglomeration
- B. Turbulent agglomeration
- C. Electrostatic agglomeration
- D. Sonic agglomeration
- E. Condensation

$$D_{pm} = \left[\frac{18\mu V}{LW(\rho_p - \rho_g)g}\right]^{1/2} \qquad \text{(A-1)}$$

where D_{pm} = diameter of the smallest size particle that is completely settled out,

ρ_p = particle density,

ρ_g = fluid density,

g = local gravitational constant,

μ = absolute viscosity,

L = length of chamber,

V = volumetric flow rate of the gas at the actual temperature and pressure, and

W = width of chamber.

Examination of Eq. (A-1) shows that in theory a very large settling chamber would give sufficient time for even small particles to settle out. In practice, space limitations restrict the use of settling chambers to large particles.

The efficiency of a simple settling chamber can be improved by giving particles a downward momentum in addition to the gravity settling effect. The number of possible designs incorporating this principle is very great, varying from a simple baffle in the chamber to specially designed jets which give accelerated settling. While momentum collectors do improve overall collection efficiency, they do not significantly enhance the collection of fine particles.

Centrifugal Force

Particulate matter is separated from gas in a cyclone by centrifugal force, or radial force, tending to drive the particles (against the resistance of motion by the gas) to the cyclone wall. The radial force imparted to the particle is

$$F_s = \frac{m_p \, v_{tp}^2}{g \cdot r} \quad , \qquad \text{(A-2)}$$

where F_s = radial separating force,

m_p = particle mass,

v_{tp} = tangential velocity of particle,

g = gravitational constant, and

r = radius of rotation.

The tangential velocity of the particle is theoretically lower than that of the gas in which it is suspended; but, in considering fine particles, the two velocities are equal for all practical purposes and $v_{tp} = v_{tg}$.

Equation A-2 can also be written in the form

$$F_s = \frac{\beta \rho_p D_p^3 v_{tp}^2}{gr \; r_f^{2n}} \quad , \qquad \text{(A-3)}$$

where β = volume shape factor, dimensionless,

ρ_p = particle density,

D_p = particle diameter,

$r_f = \frac{r}{r_s}$ (ratio of radius of rotation to the radius of confining structure), and

n = exponent, dimensionless

The force resisting particle motion is given by Stokes' law

$$F_r = C\mu D_p v_{p-g} \quad , \qquad \text{(A-4)}$$

where F_r = frictional resistance to flow,

C = Cunningham factor,

v_{p-g} = particle velocity with respect to gas, and

μ = gas viscosity.

The ratio of the separating force to the resisting force

$$\frac{F_s}{F_r} = \frac{\beta \rho_p D_p^2 \left(v_{tp}\right)^2}{Cg\mu v_{p-g} r r_f^{2n}} \qquad \text{(A-6)}$$

provides an indication of the relative ability to remove various size particles in a cyclone. Since the force ratio varies with D_p^2 , large diameter particles are more readily separated in a cyclone. Commercial cyclones are effective in collecting particles down to about 10 microns, and carefully designed units can collect particles down to about 2-5 microns.

Aerodynamic Capture

Aerodynamic capture of particles involves the collection of particles by collecting bodies (e.g., fibers, packing, droplets, etc.). To utilize aerodynamic capture, the gas stream is brought near the collecting bodies and then a number of short-range mechanisms accomplish the actual collection. The most effective mechanisms are: inertial impaction, interception, diffusion, and electrostatic attraction. The relative importance of each mechanism varies with the size and velocity of the particles and the collecting body,itself.

Inertial Impaction

The effectiveness of inertial impaction is a function of the inertial impaction parameter which arises out of the force balance equations of fluid resistance opposing the motion of the particle. The inertial impaction parameter is defined as

$$N_I = \frac{Cv\rho_p D_p^2}{18\mu \, D_c} \quad , \qquad \text{(A-6)}$$

where C is Cunningham correction factor for Stokes' law, v is particle velocity downstream, ρ_p is particle density and μ is fluid viscosity, D_p = particle diameter, and D_c = diameter of collecting body.

Ranz, Wong and Johnstone[1] and other investigators have shown that the collection efficiency of inertial impaction is a function of the impaction parameter and that the impaction parameter (N_I) must exceed 4 for collection efficiencies to exceed 90%. For a specific particulate system, $C\rho_p/18\mu$ will be a constant and to achieve a high collection efficiency of fine particles, only the particle velocity and the diameter of the collecting body can be varied to increase collection efficiency. Assuming unit density particles and typical gas viscosities, the necessary ratio of v/D_c required to result in a value of N_I exceeding 4 is shown in Figure A-1 as a function of particle size. The cgs unit system was used in deriving the data shown in Figure A-1. Figure A-2 shows the particle velocity required for high collection as a function of the diameter of the collecting body and the diameter of the particle to be collected. It is apparent from Figure A-2 that in order to collect submicron particles efficiently by inertial impaction, it is necessary to use high velocities and small collecting bodies.

Interception

Whenever the streamline along which the particle approaches a collecting body passes within a distance of one-half the particle diameter from the body, interception of the particle by the collecting body will occur. This mechanism would never occur alone except as a limiting case for particles of low density. However, it should be taken into account as a boundary condition to be met along with other aerodynamic capture mechanisms.

Using Langmuir's viscous flow equation, Ranz[2] obtained the interception collection efficiency of a cylindrical target

$$\eta = A \left[2\ (1+N_R)\ \ln\ (1+N_R)\ \frac{N_R\ (2+N_R)}{(1+N_R)} \right] \qquad \text{(A-7)}$$

where $A = \dfrac{1}{2\ (2.002-\ln N_{Re})}$, and

$N_R = \dfrac{D_p}{D_c}$.

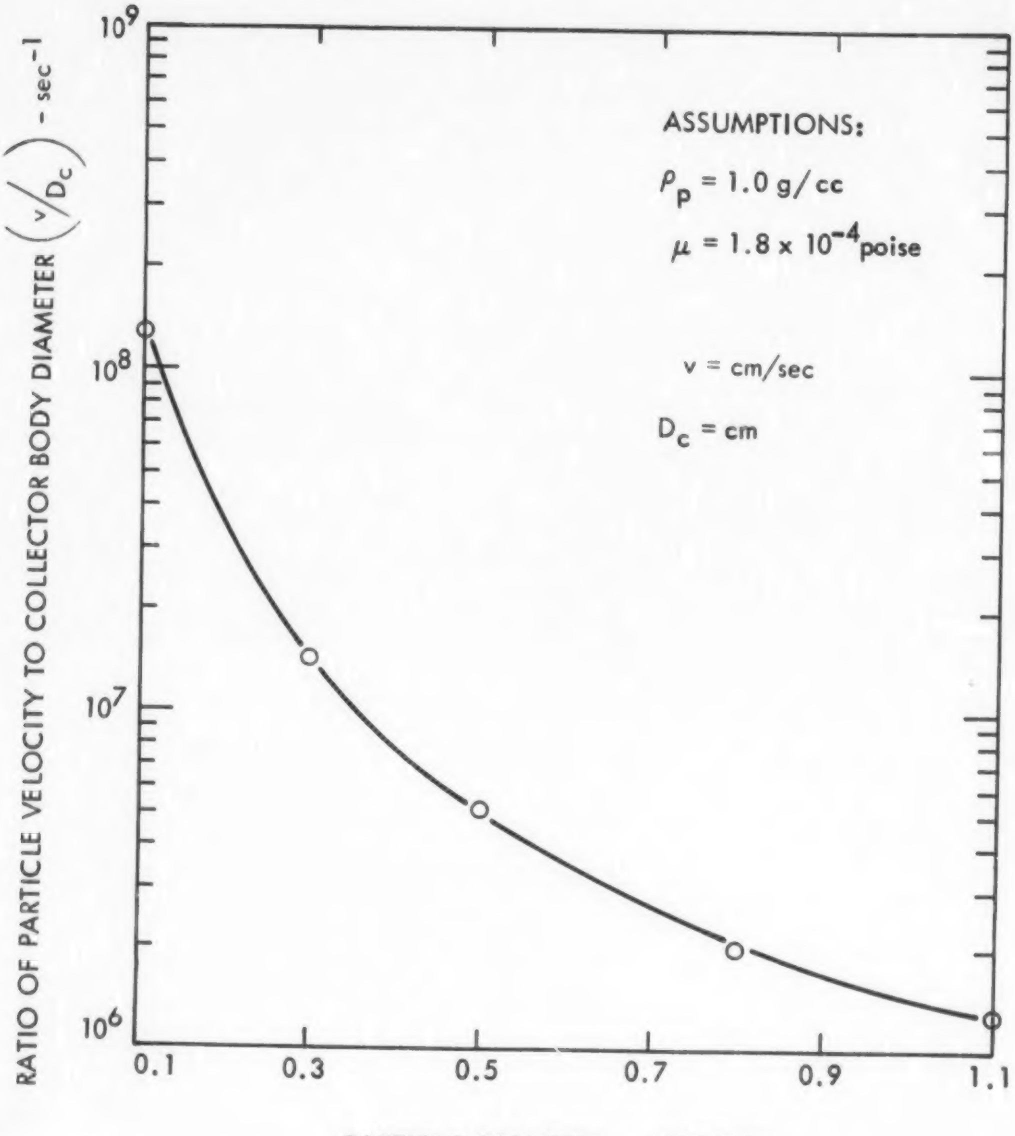

Figure A-1. Ratio of particle velocity to collector body diameter necessary to achieve 90% target efficiency for inertial impaction

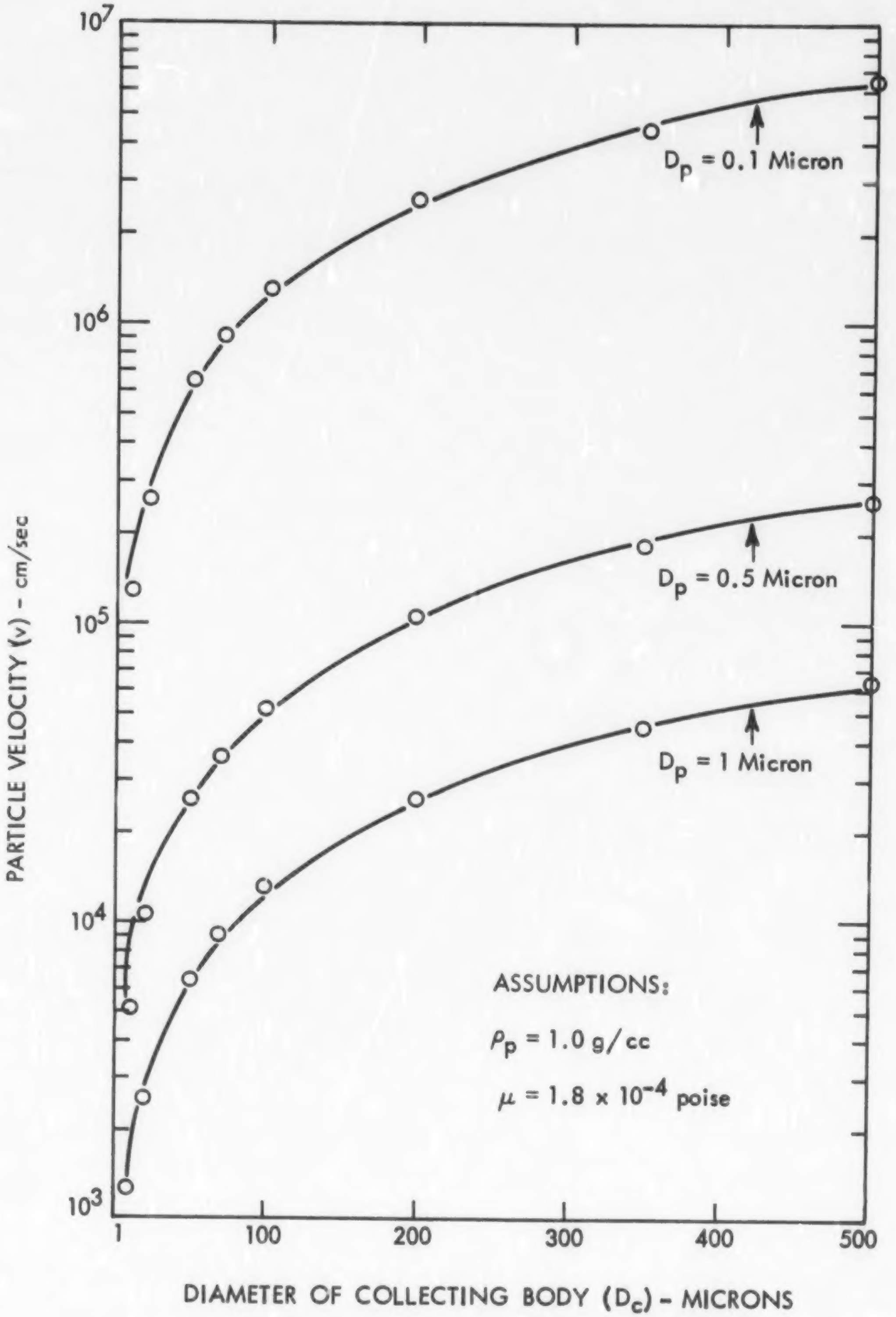

Figure A-2. Particle velocities required to achieve 90% target efficiency for inertial impaction

This equation should be used instead of the more simplified equations reported in some references because it allows for changing flow patterns with different stream velocities. Friedlander[3] found that a log-log plot of $\frac{\eta}{A}$, as calculated from this equation, against N_R was a straight line which could be represented by

$$\frac{\eta}{A} = 1.25 \, N_R^{1.82} \qquad \text{(A-8)}$$

in the range of $0.05 < N_R < 1$.

Figure A-3 presents the interception parameter as a function of N_{Re} for target efficiencies of 0.5 and 0.9. Inspection of Figure A-3 shows that for interception to be a significant mechanism for particle collection, the diameter of the collecting body must be of the same order of size as the particles to be collected. In addition, the flow velocity must be low. These restrictions imply that interception will not play a significant role in fine particle collection in most practical situations unless multiple targets are provided.

Brownian Diffusion

For very small particles, Brownian movement will be superimposed upon the flow motion of a particle. This relatively slow diffusional velocity may be sufficient to cause the particle to come into contact with the collector if the particle passes close enough to the collecting body and remains there for a long enough time.

Researchers working in this area have developed expressions for the target efficiencies due to Brownian diffusion which indicate that the target efficiency is an inverse function of the Peclet number. The Peclet number is defined by Eq. (A-9)

$$N_{Pe} = \frac{v_g D_c}{D_{BM}} , \qquad \text{(A-9)}$$

where D_{BM} = particle diffusion coefficient.

Since the diffusion coefficient is an inverse function of the particle size, the Peclet number can also be written as

$$N_{Pe} \propto v_g D_c D_p \ . \qquad \text{(A-10)}$$

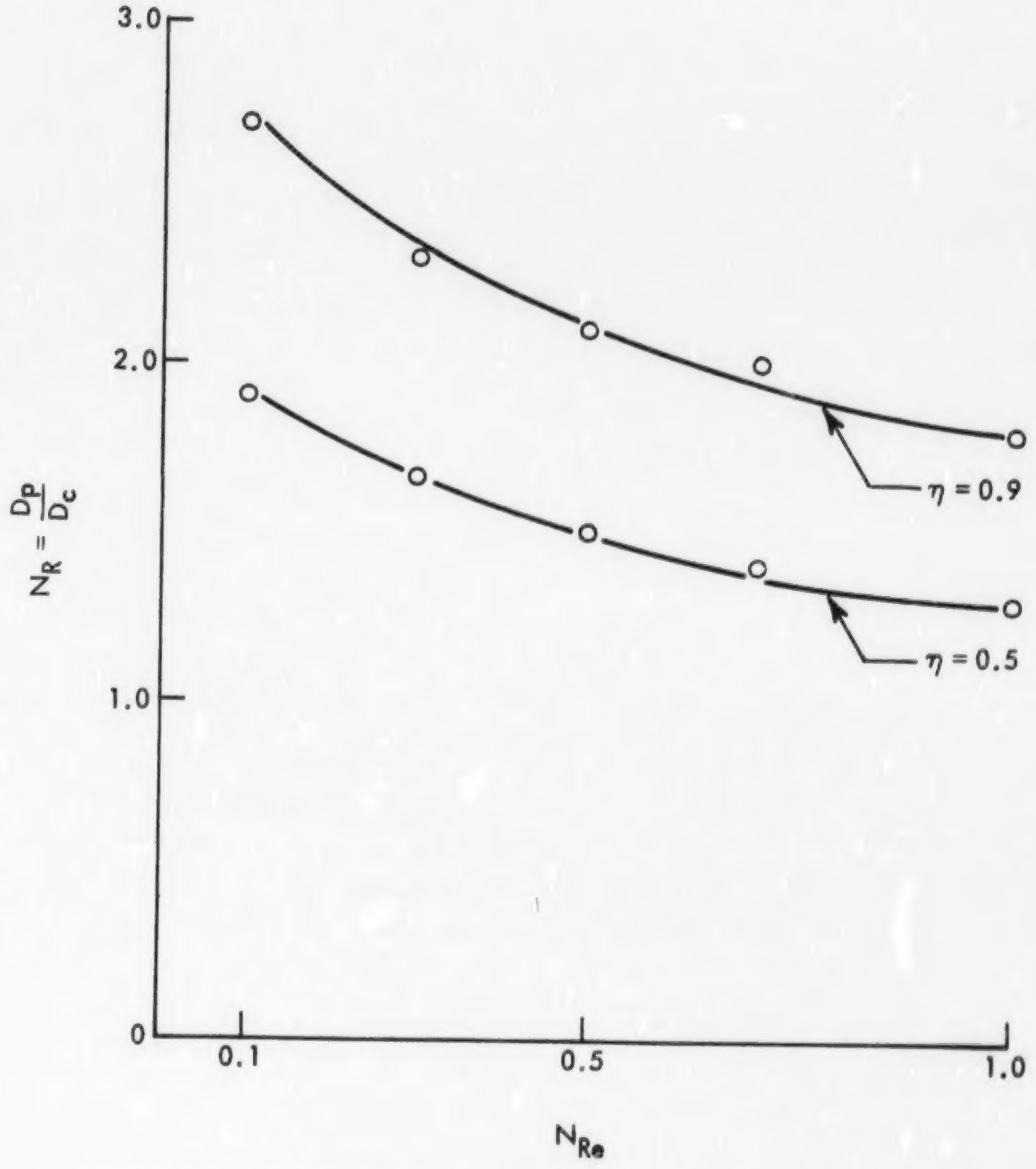

Figure A-3. Interception parameter as a function of Reynolds Number for selected target efficiencies

Figure A-4 presents graphical solutions to the equations for target efficiency developed by Ranz,[2] Friedlander[3] and Langmiur.[4] Inspection of Figure A-4 indicates that the collection efficiency attributable to this mechanism is not significant if the value of N_{Pe} is much above 10. In most situations, particle collection by Brownian diffusion will be of importance only for particles less than 0.5 micron in diameter.

Electrostatic Attraction

When an aerosol particle, or a stationary object in a flow stream, is electrically charged, or when both the particle and the object carry electric charges, the trajectories of the aerosol particle past the object are affected usually with an increase in the number of particles colliding with the object.

Ranz and Wong[5] and Kraemer and Johnstone[6] defined the dimensionless force ratios given by Eqs. (A-11) and (A-12) to characterize the forces between an aerosol particle in the absence of a field across a filter.

$$K_E = \frac{Cq_p q_f}{3\pi\mu\epsilon_o D_p v_{p-c}} \qquad \text{(A-11)}$$

$$K_I = \frac{2}{3} \left(\frac{\epsilon_p - \epsilon_f}{\epsilon_p + 2\epsilon_f}\right) \left(\frac{CD_p^2 q_f^2}{\epsilon_o \mu v_{p-c} D_C}\right) \qquad \text{(A-12)}$$

where ϵ_p and ϵ_f are dielectric constants of the particle and the gas and q_p and q_f are electrostatic charges for the particle and the collector, ϵ_o is permittivity of free space and μ is viscosity of the air. Equation (A-11) describes the interaction of a charged particle and collector, and Eq. (A-12) describes the interaction between a charged collector and a dielectric particle on which the collector induces a charge.

Parameters K_E and K_I may be considered ratios of the electric force at the surface of the collector to the fluid resistance caused by a relative particle velocity of v_{p-c} with respect to the collector. It is noted that when q_p and q_f are of the same sign, K_E is positive and collection efficiency decreases. Target efficiency by these mechanisms is negligible when the corresponding parameter is much less than 10^{-2} and is of the order of unity when the parameter is of the order of unity.

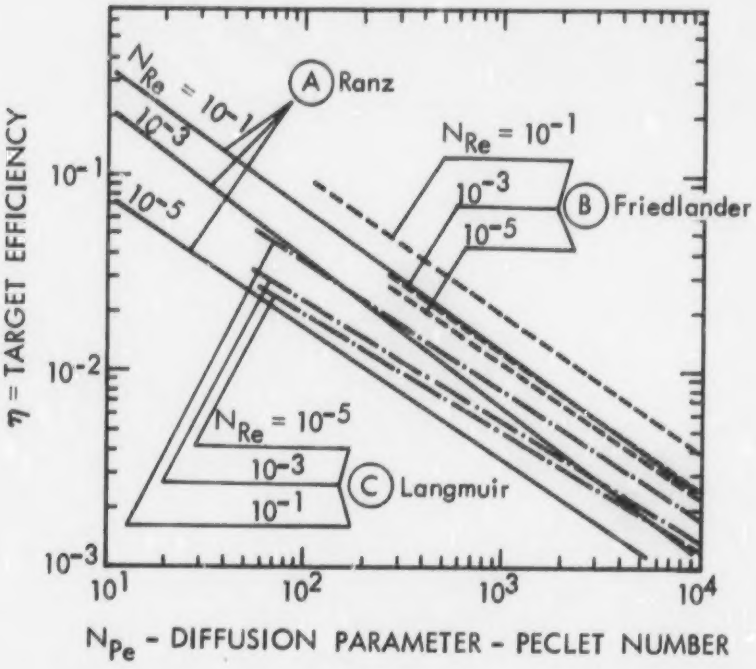

Figure A-4. Target efficiency by diffusion on an isolated cylinder

Kraemer and Johnstone[6] suggest that target efficiencies can be expressed for induced electrostatic attraction by

$$\eta \approx \left(\frac{15\pi}{8} K_I \right)^{0.4} \qquad \text{(A-13)}$$

and for charged particle and collector electrostatic attraction by

$$\eta \approx - 4 K_E \qquad \text{(A-14)}$$

based upon experimental data for a spherical collector.

COMPARISON OF AERODYNAMIC CAPTURE FORCES

Although the forces of the various aerodynamic capture mechanisms are additive, the resulting individual efficiencies are not directly additive. Each mechanism will contribute to a total efficiency, however, and no combination of favorable mechanisms will cause an efficiency lower than that expected for any one of the favorable mechanisms. In addition, the efficiency of collection for any given mechanism will be proportional to the size of the particle and the size of the collector, and to the particle-collector differential velocity in approximately the same manner that the parameter characterizing that mechanism is proportional to D_p , D_c , and v_{p-c} , by definition.

The approximate target collection efficiencies for spheres calculated by the foregoing equations are shown in Figure A-5. Inspection of Figure A-5 shows that single target efficiencies for electrical forces are generally larger than those for impaction, interception and diffusion at low velocities.

FLUX FORCES

Particles can be collected by forces which result from electrical, temperature, and concentration gradients, from the flux of matter or energy, and from a magnetic field. This group of forces, often termed flux forces, are attractive for the collection of fine particles, because the magnitude of the flux forces does not approach zero as the size of the particles to be collected approaches the submicron range. Individual flux forces are discussed in the following sections.

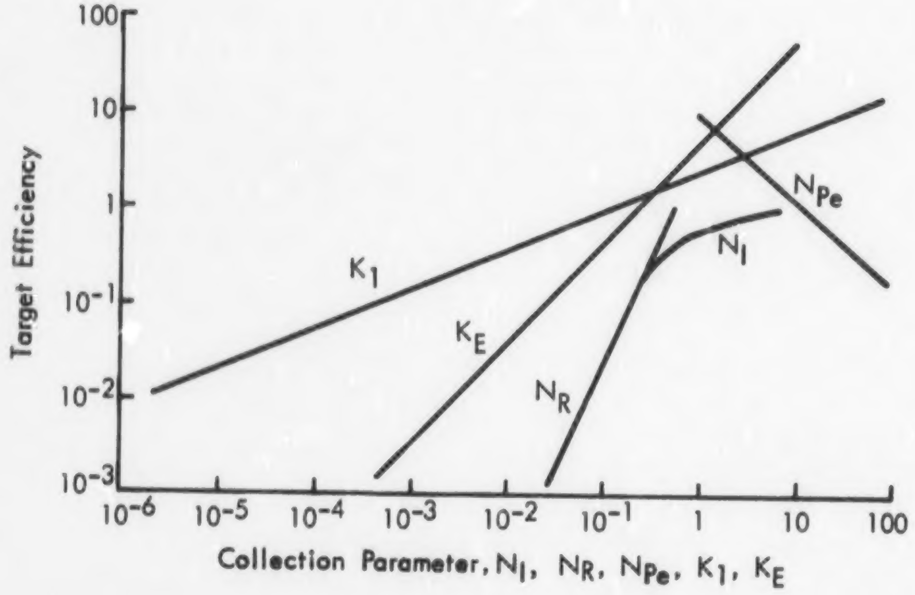

Figure A-5. Approximate solutions of equations for target efficiencies

Electrical Forces (Electrophoresis)

If charged particles are subjected to an unidirectional electric field, they move towards the electrodes and are deposited. The motion or migration of the particles in the field is termed electrophoresis. In the absence of turbulence or other aerodynamic effects, the migration velocity ω resulting from the electrostatic force can be obtained from Stokes' law and is given by

$$\omega = \frac{qE}{6\pi r_p \mu} \qquad \text{(A-15)}$$

where q is the charge on the particle, E is the strength of the electric field, r_p is the particle radius and μ is the viscosity of the gas. This expression neglects second order electrostatic effects such as the polarizability of the particle, and assumes that a spherical particle is moving in laminar flow ($N_{Re} < 1$). Both of these assumptions are normally adequate.[7] It is clear from Eq. (A-15) that for a given particle size the only practical variables affecting the migration velocity are the electric field strength and the charge.

To secure rapid and efficient deposition of particles, forced charging of particles may be adopted and this forms the basis of electrostatic precipitators. The electric field strength is determined by the configuration of the specific control device. The charge on a particle is a very strong function of the particle size and particle characteristics as well as depending on the field strength and free charge density. Both field charging and diffusion charging occur in electrostatic precipitators with diffusion charging dominating for particles less than 1 micron in radius.

Some fairly refined theories for the two charging mechanisms, field charging and diffusion charging, have been developed and yield results which are in reasonable agreement with experimental data. These theories and available experimental evidence show a minimum in the charging rate for particles in the 0.1-0.5 μm range. However, the calculated particle migration velocities for particles in this range obtained by assuming reasonable fields, charge densities and residence times, as shown in Figure A-6, are nevertheless quite large. It would seem that electrostatic devices could be devised which could utilize such large particle migration velocities for submicron particulate control.

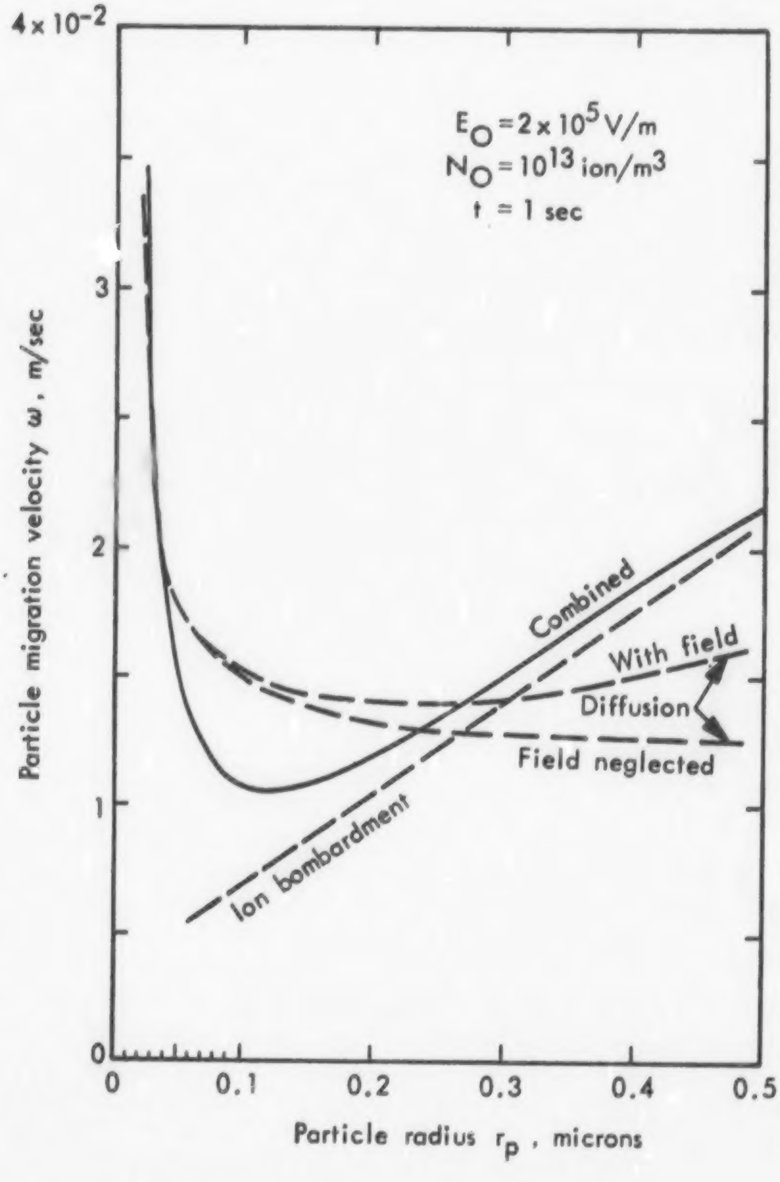

Figure A-6. Calculated particle migration velocities for submicron particles7/

Thermal Forces (Thermophoresis)

Particles can be removed from a gas stream by the use of a temperature gradient. The force which causes particle motion results from momentum differences imparted to the particle on opposite sides. The hotter (and thus faster) molecules colliding with the particle will impart a higher momentum to the particle than the cooler (slower) molecules. Aerosol particles will then drift in the thermal gradient toward the cold surface. The motion of aerosol particles associated with a temperature gradient is called thermophoresis.

Theoretical models for thermophoresis have been developed by Waldmann,[8/] Epstein,[9/] Brock,[10/] Jacobsen and Brock[11/] and Derjaquin and Bakanov.[12/] Thermal forces (i.e., radiometric forces), like other interactions between gases and particles, depend on the Knudsen number (λ/r_p), where λ = mean free path of gas molecule and r_p = particle radius .

A number of equations have been developed to calculate the velocity of a particle due to the thermophoretic force. All these equations can be expressed in one general form:

$$v_T = - K \frac{\mu}{\rho_g T} \Delta T \qquad \text{(A-16)}$$

and differ in the definition of K . The factor K allows for the effects of the thermal conductivities of the particulate material and gas and includes various accommodation coefficients which are not readily measured or evaluated *a priori*. In the simple theories K is independent of particle size while in the more complicated theories K also depends on particle size. Table A-2 summarizes various equations that have been developed for the thermophoretic velocity and the conditions for which they are applicable.

Figure A-7 presents the results of experimental measurements of the thermophoretic velocity reported by Goldsmith and May[13/] and Rosenblatt and La Mer.[14/] The thermal velocity is shown as a function of $\frac{300}{T}\frac{dT}{dX}$ where T is the mean absolute temperature between hot and cold plates and dT/dX is the temperature gradient across the plates.

Table A-2. EQUATIONS FOR THERMOPHORETIC VELOCITY

Investigator	Thermophoretic Velocity Equation	Range of Applicability	Comments
Waldmann	$v_T = - \frac{6\mu}{(8 + \pi\alpha)T\rho_g} \Delta T$	$r_p << \lambda$	Shows good agreement with experimental data
Epstein	$v_T = - \frac{3}{2} \frac{\mu}{\rho_g T} \left[\frac{k_g}{2k_g + k_p}\right] \Delta T$	$\lambda << r_p$	Agrees with experimental measurements for particles of low thermal conductivity ($k_p/k_g \leq 10$)
Brock	$v_T = - \frac{3}{2} \frac{\mu\ C'}{\rho_g T} \left[\frac{1}{1 + \frac{6C_m\lambda}{d_p}}\right] \left\{\frac{\frac{k_g}{k_p} + C_t \frac{2\lambda}{d_p}}{1 + 2\ k_g/k_p + 4\ C_t\ \lambda/d_p}\right\} \Delta T$	$\lambda << r_p$	Agrees with experimental results for both good and poor conductors to within $\approx 25\%$
Derjaguin and Bakanov	$v_T = - \frac{(4\ k_g + 0.5\ k_p)}{(2\ k_g + k_p)} \frac{\mu}{\rho_g T} \Delta T$	$\lambda << r_p$	Agrees well with experimental results

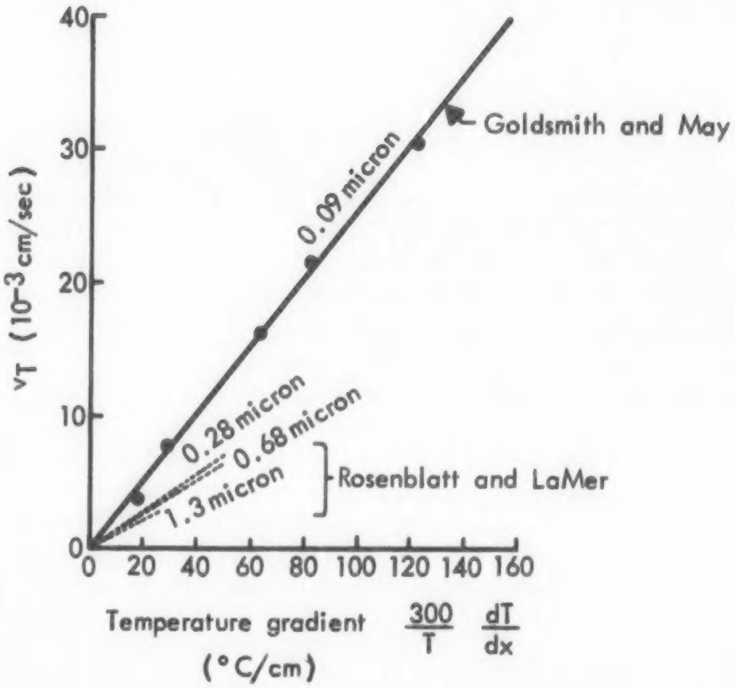

Figure A-7. The thermophoretic velocity in air as a function of temperature gradient

Theoretical calculations as well as experimental measurements such as those shown in Figure A-7 indicate that the thermophoretic velocity is quite low and long residence times are required to accomplish significant particle separation at reasonable temperature gradients. Even at temperature gradients of 10^3°C/cm, the thermal velocity is only about 0.1 cm/sec (0.04 in/sec). The large space requirements coupled with the high cost of maintaining the required temperature gradient has resulted in no industrial applications of thermal precipitators.

However, thermal forces might be exploited to enhance the performance of certain types of control devices. The deposition of particles from a hot gas in a cooled, packed bed, is an instance in which thermal forces may improve collection efficiency. Thring and Strauss report that experiments have shown that when a packed bed is initially cold, particle collection is more nearly complete.[15] Strauss also estimated that, since the passages in a bed are narrow, a temperature difference of 50°C might give rise to a temperature gradient of 1000°C/cm in the passages. Strauss's calculations show that this would result in the deposition of 98.8% of the particles of 0.1 micron diameter in a 9 in. deep bed.[16] Thring and Strauss proposed to cool the packed bed by using it as an air preheater in which another gas is heated as it cools the bed.[16]

Diffusion Forces (Diffusiophoresis)

In a concentration gradient, which is accompanied by diffusion but not necessarily by net motion of the gas phase, the heavier molecules will impart a higher momentum than the lighter molecules. If there is a net motion of the gas phase (Stefan flow), additional force is applied to the particles. The combination of forces due to Stefan flow and the concentration gradient is referred to as the diffusiophoretic force. Particle movement by this force is called diffusiophoresis.

Several theoretical models of diffusiophoresis have been developed. References 17-20 present some of the more pertinent theoretical work. Equations (A-17) and (A-18) present expressions for the diffusiophoretic velocity for the cases where $r_p \ll \lambda$ and $r_p \gg \lambda$.

$$v_p = - \frac{\mu_1}{\gamma_1} \frac{D \nabla\gamma_1}{\gamma_2} \qquad r_p << \lambda \tag{A-17}$$

$$v_p = D \frac{n(m_p - m_v)}{\rho} \frac{\Delta C}{\Delta x} \qquad r_p >> \lambda \tag{A-18}$$

where $\mu_1/\gamma_1 = \dfrac{(1+\pi a_i/8)\sqrt{m_1}}{\sqrt{m_1}(1+\pi a_i/8)\gamma_1 + (1+\pi a_2/8)\gamma_2\sqrt{m_2}}$

$\gamma_i = n_i/n$,

a_i = coefficient of thermal reflection,

n = total number of gaseous molecules per unit volume,

$\frac{\Delta C}{\Delta X}$ = vapor concentration gradient,

ρ = density of gas vapor mixture,

m_p = particle mass,

m_v = vapor molecular mass, and

D = diffusion coefficient.

Deryagin reported experimental results which show that Eq. (A-18) holds for Knudsen numbers < 0.5 and that Eq. (A-17) holds for Knudsen numbers > 0.7.[20]

Figure A-8 presents experimental measurements of the diffusiophoretic velocity in helium (4% O_2) reported by Goldsmith and May.[13] In the experiments of Goldsmith and May, a saturated salt solution was used on one wall of the vapor pressure gradient box with water on the other wall.

Diffusiophoresis should be a useful mechanism to exploit in conjunction with other mechanisms for the removal of small (< 2 microns) particulates from gas streams. Its use has the following advantages:

1. The fundamental mechanism is independent of particle size and becomes more important compared to other removal mechanisms for particles below 2 microns.

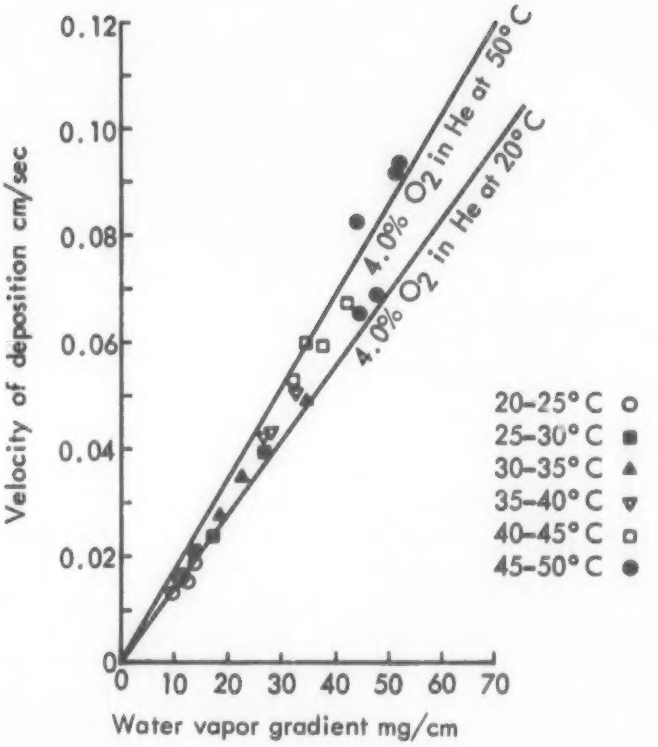

Figure A-8. The diffusiophoretic velocity in helium as a function of water-vapor pressure gradient at temperatures between 20° and 50°C

2. The particulate removal efficiency that can be expected depends on operating conditions and equipment design but can theoretically reach 100%.

To exploit the mechanism of diffusiophoresis, the collecting device must be designed such that one component in the gas phase is diffusing toward a collecting surface. The most practical case is the diffusion of water vapor toward a surface. Recent studies by Calvert, et al.[21/] have shown that diffusiophoresis can produce appreciable particle deposition under the heat and mass transfer conditions of a realistic wet scrubber.

Magnetic Forces

A force (Lorentz force) is generated when an electrical charge or an electrically charged particle moves in a magnetic field transverse to the field lines. If a dust particle carrying "n" elementary charges "q" moves with a speed v, the direction of the force will be at right angles to both the direction of the field and the direction of motion of the particle so that the particle will be diverted from its original path. As a result of the change in direction of the particle, the possibility of particle precipitation exists.

The potential for particle precipitation using the Lorentz force can be assessed by determining the terminal drift velocity of a particle in a magnetic field. The terminal velocity can be obtained by equating the Lorentz force to the resistance of the gas, calculated from the Stokes-Cunningham law:

$$nqvB = 3\pi\mu D_p v_m C \qquad \text{(A-19)}$$

where n = number of charges on particle,

q = elementary charge,

v = velocity of particle in field,

B = magnetic field strength,

μ = gas viscosity,

D_p = particle diameter,

v_m = terminal drift velocity of particle, and

C = Cunningham factor.

The left-hand term in Eq. (A-19) represents the Lorentz force and the right term the gas resistance. Equation (A-19) can be rearranged to yield the following expression for the terminal drift velocity:

$$v_m = \frac{CnqvB}{3\pi\mu D_p} \quad . \qquad \text{(A-20)}$$

Equation (A-20) indicates that the terminal drift velocity varies directly with the number of charges on a particle, the particle velocity, and the magnetic field strength and inversely with the particle diameter.

Examination of Eq. (A-20) indicates that the terminal drift velocity is less than 0.01 cm/sec for particles 0.1-1.0 micron in size except at high particle velocities and magnetic field strengths. The above theoretical considerations demonstrate that the force generated by a charged particle moving in a magnetic field is too small for use in particle separation. Furthermore, because of the low values of the terminal drift velocity at more nominal conditions of particle velocity and magnetic field strengths, the use of magnetic fields to agglomerate particles does not appear feasible.

PARTICLE AGGLOMERATION AND/OR PARTICLE GROWTH

The agglomeration or growth of fine particulates, as a step in the control of fine particulates, is in principle attractive. If large particles can be produced for reasonable energy expenditures, it may be possible to utilize devices which cause particle agglomeration or growth in conjunction with conventional control systems. Condensation is the most feasible way to achieve particle growth without agglomeration. Condensation phenomena are discussed in detail in Appendix C, and only particle agglomeration will be discussed in this appendix.

The movement of particles toward one another may be brought about solely by Brownian motion, but usually other influences play a major role, e.g., turbulence of the fluid, gravitational forces, and electrostatic forces. The following sections discuss the nature of particle agglomeration with and without the use of external forces.

Agglomeration in Absence of External Forces

When the movement of particles, leading to contact and agglomeration, can be effected only by Brownian movement (diffusion), the process is called thermal coagulation. For the general case of a polydisperse aerosol, the number of particles of radius r_2 diffusing in unit time to a fixed particle with radius r_1 is given by[22]

$$\dot{N}_{12} = 4\pi \, (D_1+D_2) \, (r_1+r_2) \, n \, (r_2,t) \qquad \text{(A-21)}$$

By expressing the diffusion coefficients in terms of the particle mobility $\emptyset$ ($\emptyset = D/kT$) and introducing the coagulation constant K_o , Eq. (A-21) can be written as

$$\dot{N}_{12} = K_o \, (r_1,r_2) \, n \, (r_2,t) \qquad \text{(A-22)}$$

where $K_o \, (r_1,r_2) = 4\pi \, (\emptyset_1+\emptyset_2) \, (r_1+r_2) \, kT$.

The basic equation for the change with time of the size distribution of aerosols due to thermal coagulation is given by Müller.[23]

$$\frac{\partial n \, (m,t)}{\partial t} = \int_0^{m/2} K \, (m_1,m-m) \, n \, (m_1,t) \, n \, (m-m_1,t) \, dm_1 - n \, (m,t) \int_0^{\infty} K \, (m,m_1) \, n \, (m_1,t) \, dm_1, \qquad \text{(2-23)}$$

where $n \, (m,t) \, dm$ is the number of aerosol particles per cubic centimeter at the time t , whose masses lie between the values m and $m + dm$, while $K \, (m_1,m_2)$ gives the value of the coagulation constant between aerosol particles of the masses m_1 and m_2 . The physical meaning of this integro-differential equation is that a particle of mass m can only come into existence if two particles with masses m_1 and $(m-m_1)$ collide: it can be integrated either from $m_1 = 0$ to $m_1 - m/2$ or from $m_1 = 0$ to $m_1 = m$. The integral value must be halved as, otherwise, each possible combination is counted twice. The second integral expresses that each particle of mass m , disappears from the fraction m to $m + dm$ after colliding with a particle of mass m_1 .

By making simpler assumptions Smoluchowski[24,25] obtained, instead of the integro-differential equation, a simple differential equation which is easily solved. If only the concentration of the total number of particles, n , is considered and the same value of K_o , the coagulation constant, is used for all particles, then the fundamental equation of coagulation becomes

$$\frac{dn}{dt} = - \frac{K_o}{2} n^2 \quad . \tag{A-24}$$

The factor 1/2 is again necessary so that each aggregate should be counted only once. The solution of Eq. (A-24) is

$$\frac{1}{n} - \frac{1}{n_o} = \frac{K_o}{2} t \text{ or } n = \frac{n_o}{1 + \frac{K_o}{2} n_o t} \tag{A-25}$$

where n_o is the initial particle number concentration at time $t = 0$.

Equation (A-25) for the particle number concentration as function of time, t , is a good approximation for the size distributions occurring in many aerosols.

The major disadvantage of thermal agglomeration with regard to particulate collection is the long time required to grow particles. The only variables which can be used to control particle-particle collision rate are temperature, gas composition and the particle concentration. The temperature and gas composition do not appear to be useful variables.

The possibility of influencing the coagulation rate of particles suspended in air by introducing a second gas or vapor has been explored in several experimental programs, and the only clear-cut results seem to be those in which the added vapor in some ways affects the shape of the particles, or in which vapor is actually being transferred between the vapor phase and the particles so that appreciable gaseous diffusion occurs (i.e., diffusiophoresis).

One could conceivably change the particle distribution and concentration by seeding the particle suspension with large particulates to act as "agglomeration sites," but this does not appear very useful considering the n^2 dependence of the total agglomeration rate. Thus, thermal agglomeration is not a viable approach to augmenting the ability of control systems to control fine particulate emissions.

Turbulent Agglomeration

Turbulence increases the relative velocities among particulates which in turn increases the chance of particulate collision. Theoretical studies on the coagulation of aerosols in turbulent flow have been conducted by Levich,[26] East and Marshall,[27] Tunitskii,[28] Obukhov and Yaglon,[29] and Beal.[30]

Levich discusses coagulation effected by fluctuations having a scale of the same order as the particle size, which is appreciably less than the internal scale of tubulence λ_o. Levich derived the following equation for the coagulation rate

$$\psi = 32\pi r_p^3 \beta n_o \approx 25 \left(\frac{\varepsilon}{\gamma}\right)^{1/2} r_p^3 n_o \qquad \text{(A-26)}$$

where β = coagulation constant,

γ = kinematic viscosity, and

ε = rate of dissipation of turbulent energy per gram of medium $\left[\lambda_o \approx \left(\frac{\gamma^3}{\varepsilon}\right)^{1/4}\right]$.

The ratio of the constants of turbulent and thermal coagulation for this case is

$$A = K_1 \left(\frac{\varepsilon}{\nu}\right)^{1/2} \left(r_p^2/D\right) \qquad \text{(A-27)}$$

where K_1 is a constant of the order 0.1-0.5. For particles 1 μm in radius $r_p^2/D \approx 0.1$. Hence it follows that for the coagulation of such particles to be accelerated noticeably by turbulence $\sqrt{\varepsilon/\nu}$ must be about 100 and λ_o about 0.1 cm. This in turn requires a very high velocity. Under these conditions, the effect of turbulent coagulation is negligible for particles of radius 0.1 μm while for particles of 10 μm it is very large.

Beal has studied the case where the sink particle is larger than the turbulent microscale ($r_p > \lambda_o$) and has derived the following equation for the collision rate per unit area of sink particle[30]

$$j = \frac{7}{3} \beta_1 \lambda_o^{2/3} \left(\frac{\varepsilon}{\gamma}\right)^{1/2} r_p^{1/3} n_o \qquad \text{(A-28)}$$

where β_1 = constant, ~ 1/4 .

For this case the ratio of constants of turbulent and Brownian diffusion coagulation is

$$A = \frac{7}{12} \lambda_o^{2/3} \left(\frac{\varepsilon}{\gamma}\right)^{1/2} r_p^{4/3} / D \qquad \text{(A-29)}$$

Figures A-9 and A-10 present some of the results of Beal's theoretical calculations. As shown in Figure A-9, the "exact" solution of the diffusion equation is asymptotic to the solutions based on either Brownian motion or turbulent diffusion alone and does not differ very much from a simple sum of these solutions. Figure A-10 presents the normalized coagulation constant, K , as a function of particle diameter.

Beal's analysis has several limitations. Only the steady-state solution of the diffusion equation was obtained, only interactions among particles of equal size were considered, and all particles were assumed to stick together on impact. The last assumption is the most tenuous.

Experimental study of the rate of agglomeration in the presence of turbulence is difficult because turbulence also accelerates the deposition of particles on walls. The rate of deposition increases with particle size so that the assessment of the course of agglomeration is complicated. Experiments by Yoder and Silverman are the only results that appear to be subject to any rigorous analysis.[31] These investigators performed experiments to obtain data on the deposition and agglomeration of particles in turbulent air flow. In their experimental design, deposition and agglomeration were occurring simultaneously, and their basic problem was to separate the two effects. They did this by measuring both the total number concentration and the fraction of particles which had agglomerated at the inlet and outlet of their test section. By applying certain theoretical concepts, they could then infer the separate effects of both deposition and agglomeration from the measured parameters. They did not, however, make any direct observation of either phenomenon.

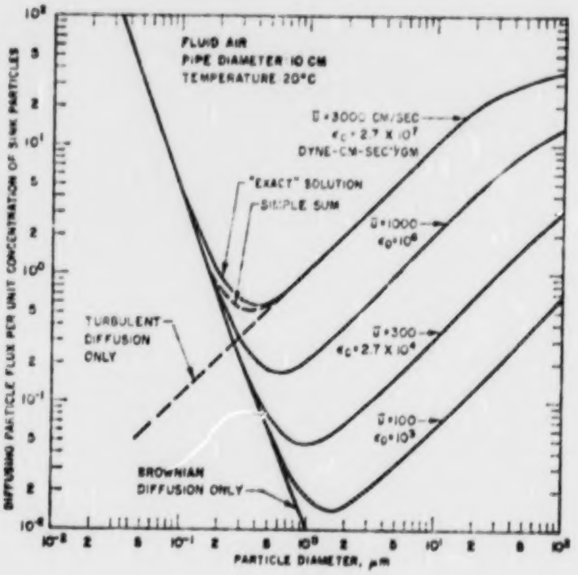

Figure A-9. Particle agglomeration flux for various particle diameters and fluid velocities

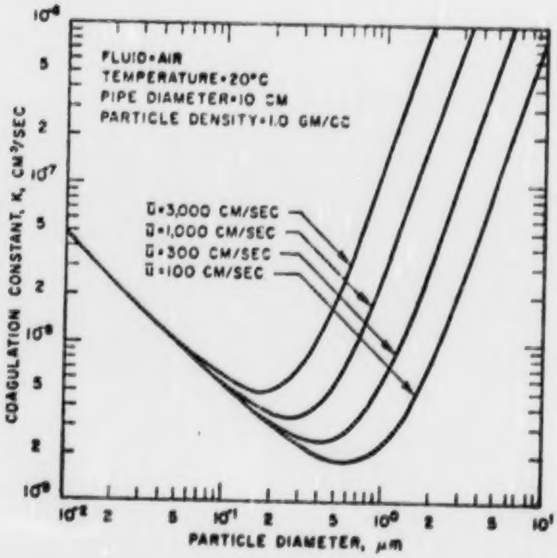

Figure A-10. Coagulation constants for various particle diameters and fluid velocities

Beal utilized the data of Yoder and Silverman for a comparison with his theoretical predictions of particle agglomeration. Figure A-11 presents this comparison. The agreement is reasonably good for the 0.8 μm particles, but poor for the 0.26 μm particles. No adequate explanation of the difference in magnitude between the observed and predicted values of the coagulation constant was offered by Beal. A general discussion of the difficulties encountered in the experimental determination of turbulent agglomeration coefficients is presented by Fuchs.32/

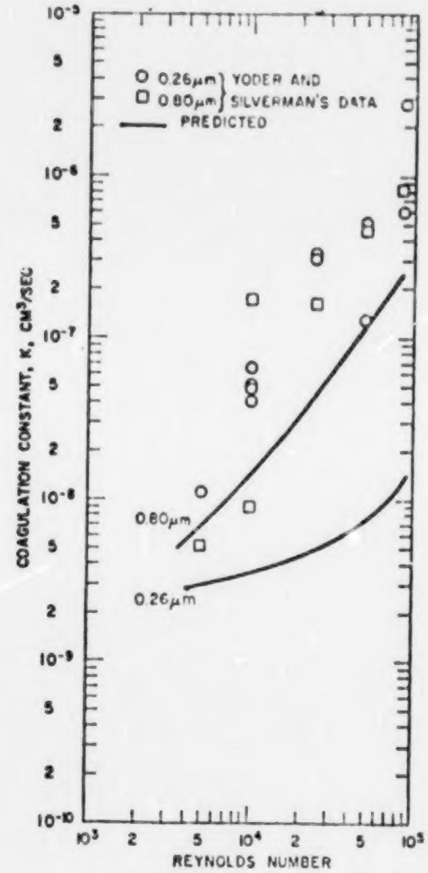

Figure A-11. Comparison of theoretical predictions with Yoder and Silverman's agglomeration data.

Figures A-9 and A-10 indicate that turbulence does not significantly enhance the coagulation constants for particles less than 0.2 μm in diameter, but can increase the coagulation constant of 0.5 μm particles by about a factor of 10 and 1 μm particles by a factor of 10^2. The energy expended to accomplish this increase is about $2.7 \times 10^7 \frac{\text{dyne-cm-sec}^{-1}}{\text{g}}$ or 0.004 hp/g. This is equivalent to about 40 hp/1,000 ft^{-3}. If this energy is expended over a period of 1 min, a 0.5 μm particle might be grown to about 2-3 μm. This is an extremely high energy consumption and, therefore, turbulent agglomeration does not appear attractive if an external source is required to provide the turbulence.

Agglomeration in Sonic Fields

A potentially effective way of rapidly agglomerating fine particles to a larger size is to pass the aerosol through a sonic field. Several different effects are responsible for the enhanced agglomeration rate due to sonic forces including (1) collection of the particles at the antinodes in the sonic standing wave (due to radiation pressure), (2) hydrodynamic forces between the particles and, (3) additional collisions due to the different vibrational amplitudes of different sized particles. Although no comprehensive theory is available some idea of the parametric dependence of these several forces can be obtained from standard equations.

The radiation pressure exerts a maximum force F on a small, rigid sphere in a frictionless gas which is given by the expression[33]

$$F = 5/3\pi^2 \rho_g \frac{(\Delta v)^2}{\lambda_s} r_p^3 \qquad \text{(A-30)}$$

where λ_s is the wavelength of the sonic vibration ρ_g is the gas density, and Δv is velocity amplitude of the gas relative to the particles.

The hydrodynamic potential between two particles $\psi(d)$ is given by

$$\psi(d) = \pi \rho_g r_p^6 \frac{(\Delta v)^2}{d^3} (\overline{\sin^2 \theta} - 2\, \overline{\cos^2 \theta}) \qquad \text{(A-31)}$$

where θ is the angular difference between the direction of vibration and the line between the centers of the particles and d is the distance between the particles.

The vibrational amplitudes of different size particles can be obtained from the expression of Hiedemann[34]

$$\frac{X_p}{X_g} = \frac{1}{\left[\left(\frac{\pi D_p^2 \rho_p f}{9\mu C}\right)^2 + 1\right]^{1/2}} \qquad \text{(A-32)}$$

where X_p and X_g are the vibrational amplitudes of the particle and the suspending gas and f is the frequency of vibration.

The relative importance of the three mechanisms cited above has not been determined. In fact, there is no assurance that other mechanisms are not important. It is therefore not possible to construct a theoretical model even if the equations given above could be applied to real situations. Nevertheless, it is interesting to note the functional dependence of the equations for these mechanisms. All three expressions show a strong dependence on the radii of the particles, with the forces due to radiation pressure and hydrodynamics increasing with increasing particle size and the relative vibrational amplitudes decreasing with increasing particle size. There is also a strong frequency dependence in all these expressions. Since the value of Δu drops to zero at low frequency, it can readily be seen that all three mechanisms for particulate agglomeration will become unimportant at low frequency. At high frequencies, on the other hand, the vibrational amplitude of the particles become negligible. There is therefore an optimum frequency for acoustic agglomeration which varies with particle size.

As noted in the previous paragraphs there is no usable theoretical model available for sonic agglomeration processes. There is, however, a large body of rather diverse experimental results available and Ref. 35 presents an extensive review. Several generalizations can be made from this body of literature. Since an adequate model does not exist, these generalizations, which are listed below, provide a basis for consideration of possible practical application of sonic agglomeration.

1. Sonic fields can effectively induce agglomeration in all sizes of suspended particles, including those in the submicron range.

2. All materials can be agglomerated.

3. The efficiency of the agglomeration depends upon the square of the particulate concentration. The minimum particulate loading that can be treated is usually given as 1.1-2.3 g/m^3 (0.5-1.0 grain/ft^3), although number density and mean size would appear to be more important parameters.

4. The sonic agglomeration process is strongly frequency dependent, with the optimum frequency varying with the particle size or sizes to be agglomerated. Optimum frequencies range from a few hundred to an upper limit of about 10,000 Hz.

5. The required residence time for a given degree of agglomeration varies with field intensity, and minimum field intensities of about 140 dB are required for usable residence times. For a 150-160 dB field a residence time of 5 sec is typical.

A number of industrial installations of sonic agglomeration systems are discussed in Ref. 35.

Sonic coagulation of particulates has as its principal advantage its applicability to any aerosol, including those comprised of submicron particles. The principal disadvantage of sonic coagulation is its relatively high energy requirements, which have been reported ranging from 0.05-0.7 $hp/m^3/min$ (1.5-19 hp/1,000 cfm). It is this factor which has apparently led to the virtual abandonment of sonic precipitators. However, Mednikov[35] suggests that minimum total energy requirements of 0.16-0.32 $hp/m^3/min$ (4.5-9 hp/1,000 cfm) should be achievable with optimum design. Presumably this energy requirement is based on agglomeration to a sufficient size to be removed by inertial precipitators. A second major disadvantage is the low efficiency of acoustic coagulators and their inability to handle highly dispersed suspensions. Even with long residence times sonic precipitators which incorporate inertial separators cannot treat suspensions having particle loadings of less than 1.2-2.3 g/m^3 (0.5-1.0 $grains/ft^3$), and leave a somewhat lesser quantity of particles in suspension. It is therefore necessary to augment highly dispersed suspensions with a water mist or other particles to increase the particle loading.

From the above discussion, the energy requirements of a sonic precipitator with an inertial separator or other simple filtering system seem relatively high. Water augmentation appears necessary to obtain the removal of a large fraction of the particulates. If 0.02 kg of water per cubic meter per minute is used, one would expect an increase in the power requirements of up to 0.04 $hp/m^3/min$, depending on the device used and the mean droplet size. The minimum energy requirements would then be 0.2-0.35 $hp/m^3/min$ (5.5-10 hp/1,000 cfm). Whether this is competitive with other devices capable of removing fine particles remains to be seen.

Alternatively, one should consider hybrid units. For example, sonic agglomeration could be used upstream from a conventional electrostatic precipitator. Since the particulates now need to be agglomerated to only 1-2 µm instead of 10-15 µm with an inertial separator, a reduction in acoustic energy requirements by at least a factor of 5 would be expected. Other hybrid units should also be possible.

Agglomeration of Charged Particles

One method of increasing the rate of agglomeration of fine particulates is to add a bipolar charge, either with or without an externally imposed field. With proper conditions large electrostatic forces between particulates can produce a large increase in the rate of agglomeration of submicron particulates.

Fuchs[32/] and Zebel[36/] have derived the following equation for the rate of agglomeration for charged particles:

$$-\frac{dn}{dt} = k_{em} K_o n^2 \qquad \text{(A-33)}$$

where K_o = agglomeration coefficient in the absence of charge, and

k_{em} = correction factor to allow for both particle charge and particle mean free path.

The correction factor, k_{em} is given by

$$k_{em} = \frac{N_q}{e^{N_q} - 1 + N_{me}} \qquad \text{(A-34)}$$

where $N_q = \frac{q_{p1}\, q_{p2}}{2\pi\epsilon_o \epsilon_f kT(D_{p_1} + D_{p_2})}$,

$N_{me} = N_m N_q e^{N_q}$,

$$N_m = \left[\frac{4(D_1+D_2)}{(D_{p_1}+D_{p_2})}\right]\left[\frac{4}{3kT}\left(\frac{m_1 m_2}{m_1+m_2}\right)\right]^{1/2} ,$$

k = Boltzmann's constant,

D_{p_1}, D_{p_2} = particle diameters,

m_1, m_2 = particle masses,

q_{p_1}, q_{p_2} = charge on particles in electrons,

ϵ_o = permittivity of free space,

ϵ_f = dielectric constant of gas medium,

T = temperature, and

D_1, D_2 = particle diffusion coefficients.

N_q is a parameter to allow for charge effects and N_m is a parameter to allow for slip between particles (as distinguished from slip between molecules) in the collision between two particles of different diameters D_{p_1} and D_{p_2}, diffusion coefficients D_1 and D_2 and masses m_1 and m_2.

Figures A-12, A-13, and A-14 illustrate the influence of charged particles on agglomeration for a monodisperse aerosol in which all particles have the same magnitude of charge.[37/] Figure A-12 presents the agglomeration rate in terms of number concentrations while Figure A-13 shows it in terms of mass concentration. The effect of particle charge on agglomeration rate is shown in Figure A-14. This figure shows that a unipolar charge causes a very rapid reduction in k_{em}, and hence in agglomeration rate, while the rate of increase in agglomeration rate due to ambipolar charge is not as rapid. Figure A-14 shows only the relative effect of charge on agglomeration rate for various charge levels and particle sizes. It implies a very large relative effect for large particles but tells nothing about the absolute rate directly, since the particle agglomeration rate decreases rapidly with increasing particle size for a given mass concentration. The absolute effect can be obtained by considering Figures A-13 and A-14 simultaneously.

For weakly charged monodisperse aerosols, Figure A-14 indicates that there will be little change in the agglomeration rate for fine particles. For highly charged aerosols, the agglomeration rates can be much higher (up to 100-1,000 times that of the uncharged aerosols), but will usually fall

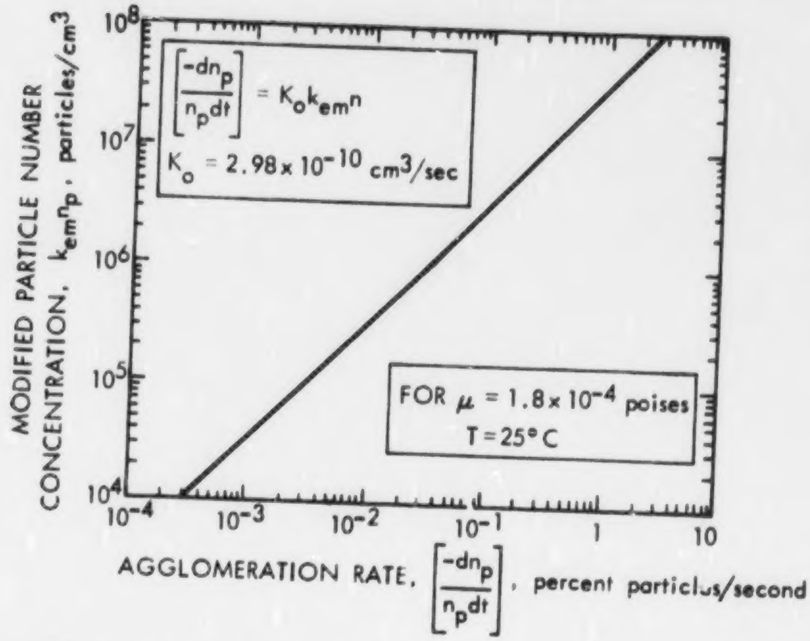

Figure A-12. Effect of particle number concentration on agglomeration rate[37]

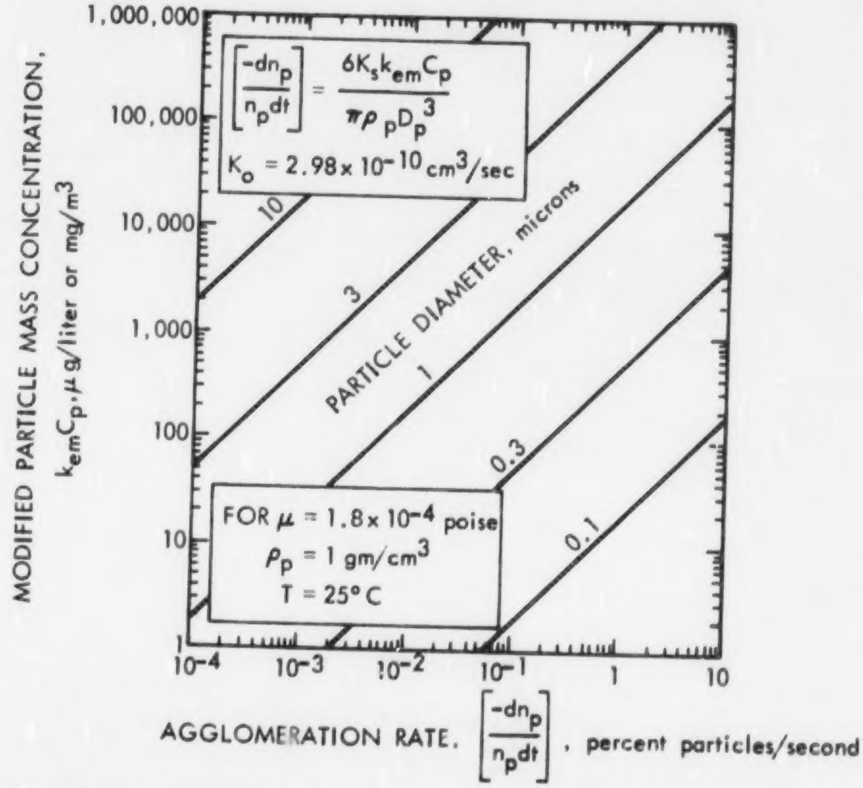

Figure A-13. Effect of particle mass concentration on agglomeration rate[37]

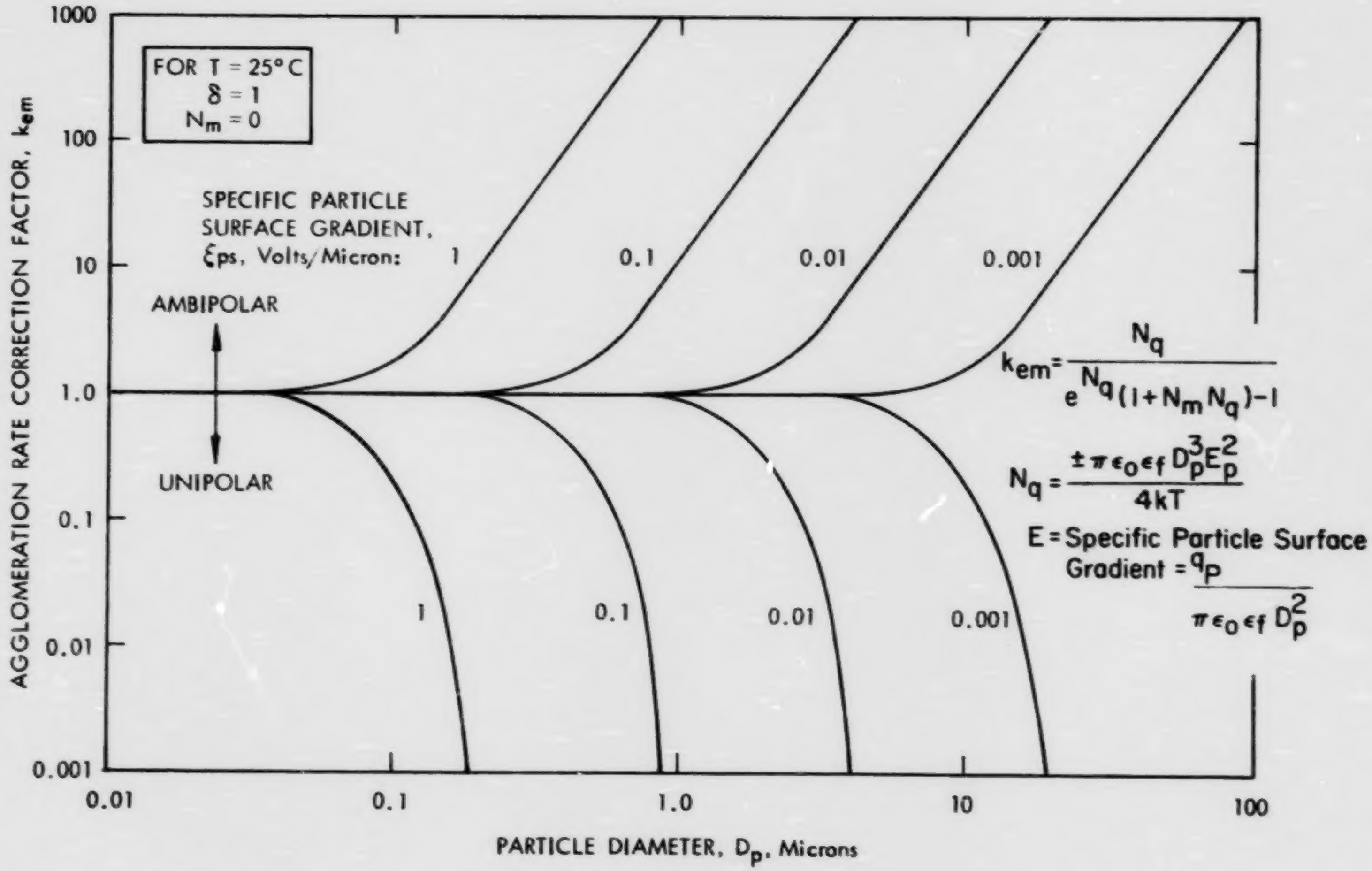

Figure A-14. Effect of particle charge on agglomeration[37/]

rapidly due to the annihilation of the charge upon agglomeration and decrease in number density. This result does not seem very promising for practical applications.

However, if we consider a bipolarly charged polydisperse aerosol containing a large number of relatively large particulates as well as the fine particulates the situation appears much more favorable because it may be possible to collect the fine particulates on the large particulates. As a result fewer steps would be required to substantially reduce the fine particulate concentration. Furthermore, the agglomeration process would result in much less charge annihilation.

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APPENDIX B

EMERGING CONTROL TECHNOLOGY--SPECIFIC CONTROL DEVICES

INTRODUCTION

A variety of collection devices touted as being effective for the collection of fine particulates, have been reported in the literature or submitted to EPA for evaluation. The devices range from laboratory-scale devices to full-scale units that have been tested on industrial sources. Several of these devices were evaluated during this study and specific systems are reviewed in the following sections of this appendix.

Steam-Hydro Air Cleaning System
Lone Star Steel
Lone Star, Texas

Lone Star Steel has recently developed a wet scrubbing system which utilizes a high-speed steam drive with injected water to accomplish the removal of particulate pollutants. The system consists of a steam nozzle, water injector, mixing tube, and twin cyclones. Normally, the system operates on energy produced by waste heat captured from the process being controlled. The heat is used to generate steam in a waste heat boiler. In installations where heat energy is low, supplemental heat may be provided. In many cases, a package steam boiler may supply all the energy. In addition to driving the system, the steam nozzle creates a draft which draws contaminated gases into the system.

Figure B-1 presents a simplified diagram of the system.1/ The first stage of cleaning is done in an optional atomizing chamber with water sprays that may be employed to cool the gas stream and remove heavy particulate. The conditioning or atomizer chamber is usually only necessary if the gas stream contains submicron particulates.

The steam nozzle, a proprietary design, surrounded by eight spray nozzles as shown in Figure B-2 is a key element in this system.2/ The exit velocity of the steam is about 1,050 m/sec (3,500 ft/sec). The function of the steam is to breakup or shear the surrounding water spray and to provide motive power for moving the gas stream through the system. The flow rate of injected water controls the cleaning efficiency. The steam flow rate has little to do with the cleaning efficiency, but some is required to shear the injected water spray.

Steam requirements as reported by Lone Star Steel range from 0.03-0.16 kg of steam per cubic meter of gas (2-10 lb/1,000 ft^3) depending on upstream process draft requirements. Water rates are 0.23 kg of H_2O/kg of gas (230 lb of H_2O/1,000 lb of gas) for the conditioning or atomizing chamber and for the spray nozzles surrounding the steam jet.

Efficiency tests have recently been performed by an EPA contractor* on a unit installed on multiple open-hearth (oxygen lanced) steel furnaces at Lone Star Steel. Figure B-3 presents a diagram of one of the units.

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* Tests performed by Southern Research Institute using impactors and a diffusion battery for particle sizing and fractional efficiency measurements.

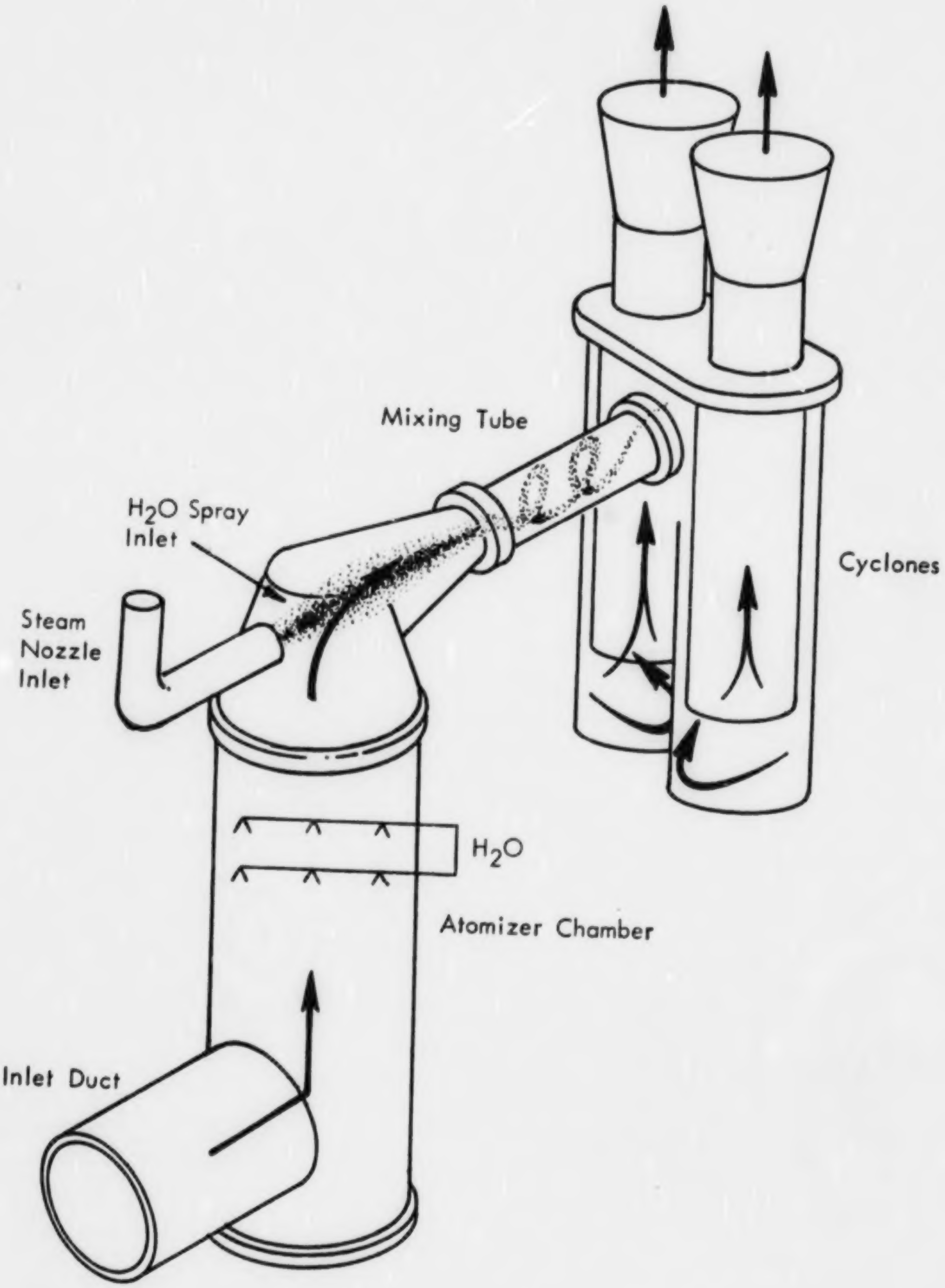

Figure B-1. Simplified diagram of Steam-Hydro Air Cleaning System

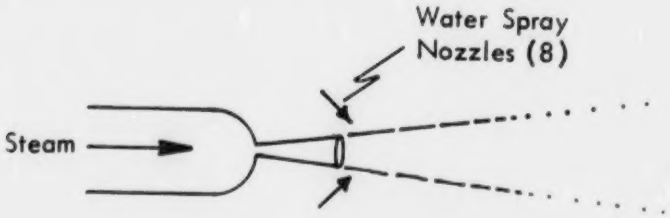

Figure B-2. Diagram of steam nozzle and water spray nozzles (Steam-Hydro Air Cleaning System)

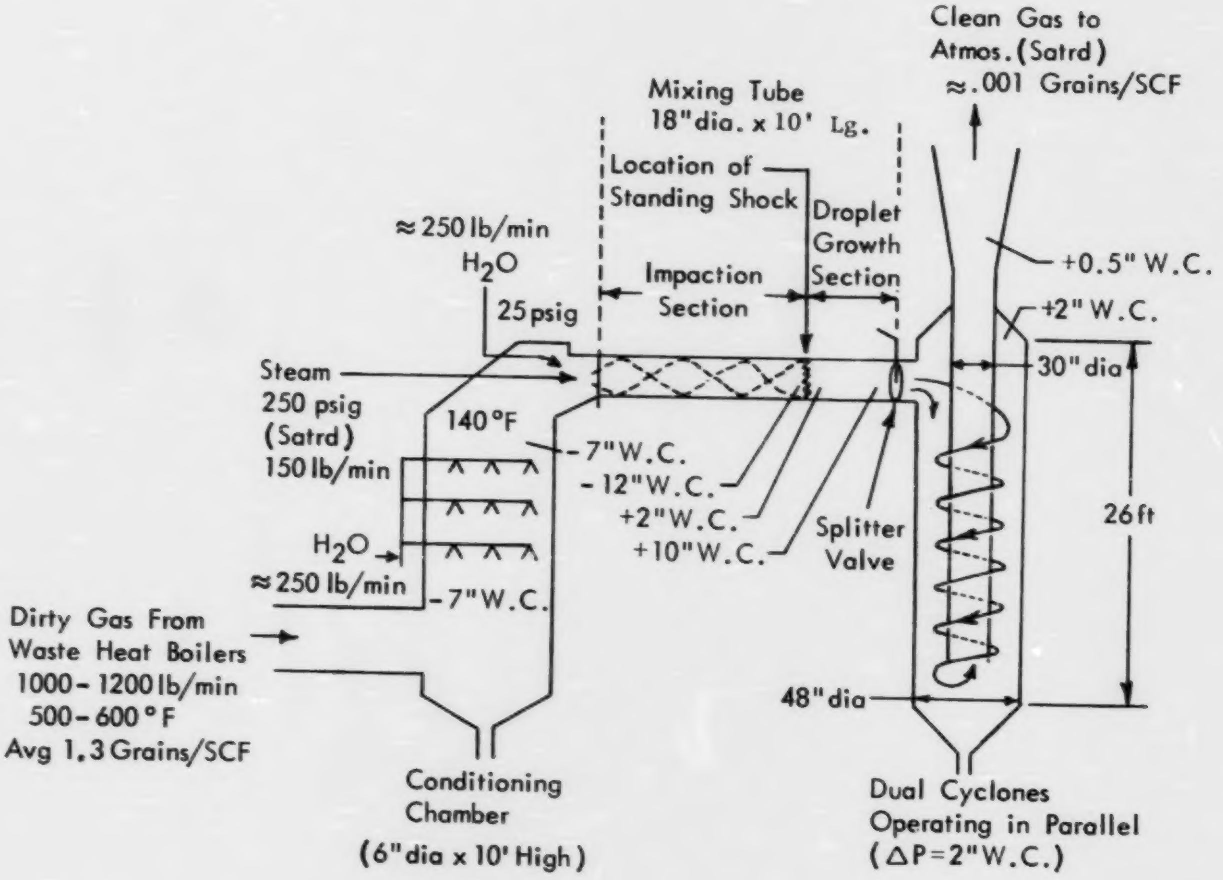

Figure B-3. Diagram of one Steam-Hydro air cleaning unit serving open-hearth furnace

Preliminary test results indicate collection efficiencies of 99.5% or greater. During the tests, inlet grain loadings averaged 2.88 g/m^3 (1.26 grains/scf), but varied from 0.23-6.86 g/m^3 (0.1-3.0 grains/scf) depending on the point in the process cycle. Outlet grain loadings ranged from 0.002-0.02 g/m^3/(0.0008-0.0089 grains/scf). The inlet size distribution of particles had a mass mean diameter of 1.5 microns and nearly all the particulates were less than 5 microns in diameter.

Capital, operating, and maintenance cost data are not available for the device. Lone Star Steel has stated that "the installed cost is more than competitive with conventional devices (excluding cost of waste heat boilers)."2/

Based on the results of the preliminary tests conducted by SRI, the Steam-Hydro system offers excellent promise as a new system for the control of fine particulate emissions. The system appears to be applicable to a wide range of sources, but primary applications are likely to be sources where waste heat is available and which emit fine particulates. Where waste heat is not sufficient to power the system, supplemental heat may be used. However, the use of supplemental heat would add to the overall cost of the system.

ADTEC Wet Scrubbing System
Aronetics, Inc.
Tullahoma, Tennessee

The ADETC system, developed by Aronetics, Inc., Tullahoma, Tennessee, is a wet scrubbing system that operates on the conventional venturi collection-mechanism of inertial impaction, but establishes the requisite particle-droplet differential velocity by utilizing waste process heat rather than external energy. The Aronetics system is shown schematically in Figure B-4.[3] Waste gas from the industrial process passes through the heat exchanger, the two-phase jet, and the separator, in that order. Water is pumped at 300 psi to a heat exchanger where heat is transferred to the water from the gas increasing the temperature of the water to the required level, usually between 300°F and 400°F. Expanding through the nozzle of the two-phase jet, partial flashing occurs (approximately 15% vaporizes), and the remaining liquid is atomized (water droplets average approximately 10 µm). Thus, a two-phase mixture of steam and small water droplets leaves the nozzle at high velocity. The dirty gas is entrained by this high velocity two-phase mixture, and in the ensuing mixing with the gas, cleaning occurs primarily by impaction. At the same time, transfer of momentum to the gas results in a pressure rise across the mixing section. This pressure rise provides the motive force to move the gas through the system.

The mixture of steam, gas, and entrained water with dust collected in cleaning, passes through the separator after discharging from the mixing section. The water with the dust is removed from the gas and steam mixture which then leaves the separator through the stack. The water with dust is discharged from the separator to the wastewater treatment subsystem. Chemicals and other treatment are applied to remove the dust and other contaminants from the water for recovery of the water and to prevent scale and corrosion in the system.

The treated water is returned to the pump for recycling and sludge is removed for disposal by other pumps not shown. Make-up water to replace water leaving the system through the stack in vapor form and with the sludge is introduced in the separator where some heat is transferred to the make-up water from the gas.

Since the transfer of momentum produces a pressure rise across the mixing section which provides the motive force to move the gas through the system, the ADTEC system does not require, nor does it include, a blower which is necessary in other cleaning systems or methods. A typical

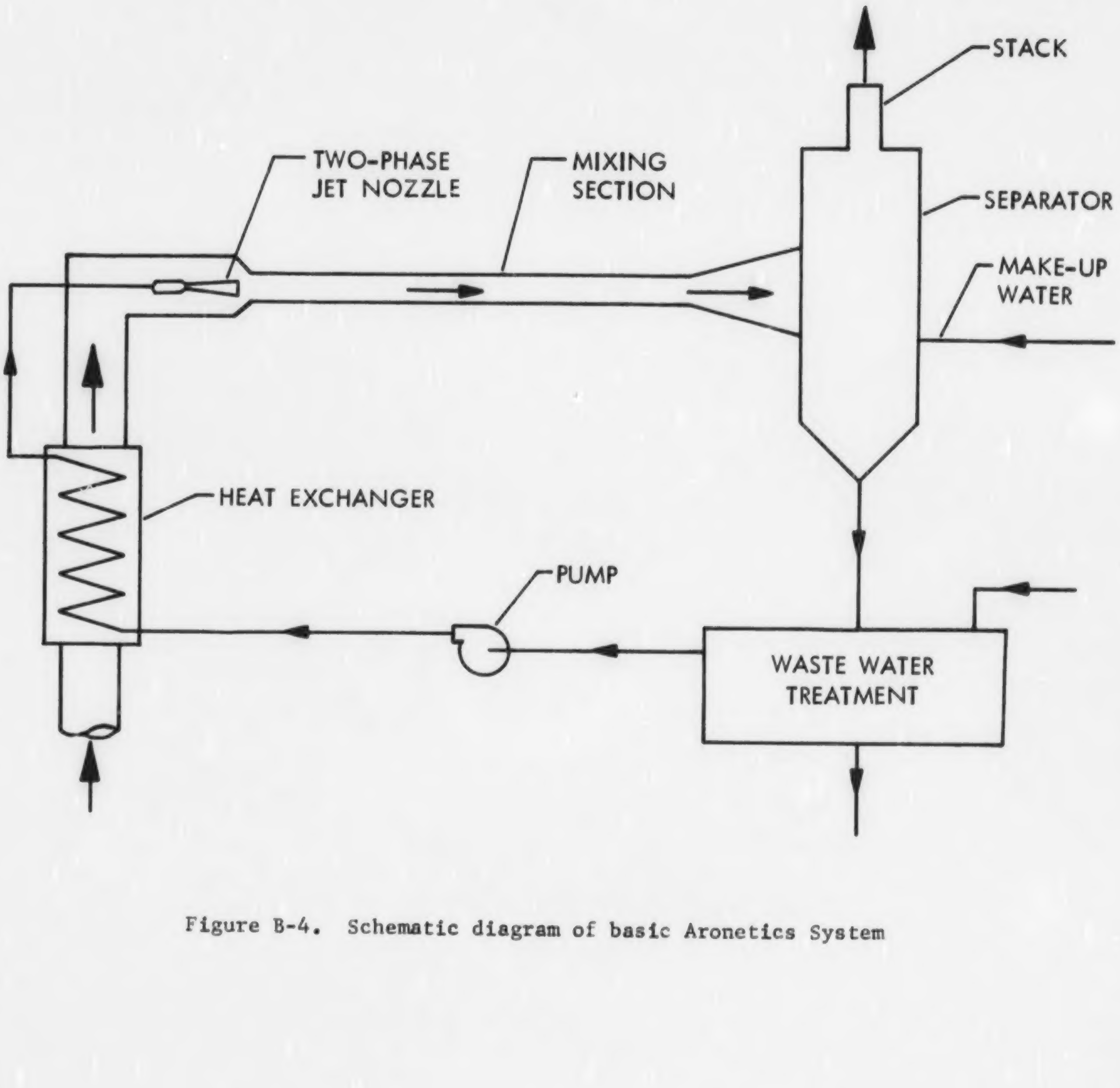

Figure B-4. Schematic diagram of basic Aronetics System pressure rise plot as a function of water temperature is shown in Figure B-5 for a water-to-gas ratio of 1-kg water per kilogram gas. System pressure loss in some cases may include 35.6 cm (14 in.) water gauge in the ducting and heat exchanger, and 20.3 cm (8 in.) water gauge in the separator for a total of 56 cm (22 in.) water gauge. From Figure B-5, a water temperature of 360°F would provide the necessary pressure rise of 56 cm (22 in.) water gauge.

Water temperature and water-to-gas mass ratio are the two principal design parameters. Values for each are selected in a specific design to meet cleaning and pumping requirements for each application. In general, fine dust will require higher temperatures and higher water-to-gas ratios.

A test unit was installed on a ferroalloy furnace of the Chromium Mining and Smelting Corporation (Chromasco) at Woodstock, Tennessee. Test results from the pilot system are given in Table B-1.[3] From left to right, the columns give the test number, the furnace product, the system configuration, the water-to-gas ratio, the water temperature, and the outlet dust loading. Several variations in equipment configuration were made during the test program. These variations are noted by a letter designation in the Aronetics system configuration column. Inlet dust loadings ranged from a low value of 0.62 g/m^3 to a high value of 19.8 g/m^3. There was no apparent effect on outlet dust loading as a result of increased inlet loading. Collection efficiencies of 99+% were reported. The sampling and analysis methods used to obtain the data shown in Table B-1 are not known.

Particle size distributions of the dust to which the results of Table B-1 apply are given in Table B-2. Furnace products during certain tests were 75% and 50% ferrosilicon. Size distributions in the reaction gas differ slightly for the two products, and both are given in Table B-2. Although all of the dust is finer than 0.5 μm, the most significant aspect of these data are the large amount, 80% plus by weight, which is < 0.1 μm. The size distributions reported in Table B-2 were obtained by optical procedures using an electron microscope.[4]

Mechanical energy consumed in pumping the water to the required pressure of 275 to 300 psi is about 0.11 $hp/m^3/min$ (3 hp/1,000 cfm) of gas while the power required in the form of heat input to the water from the gas stream exceeds 7.0 $hp/m^3/min$ (200 hp/1,000 cfm). The latter power requirement would obviously be excessive if it were not supplied by waste heat from the gas stream. Capital costs have been estimated by Aronetics to be between those of venturi scrubbers and fabric filters.

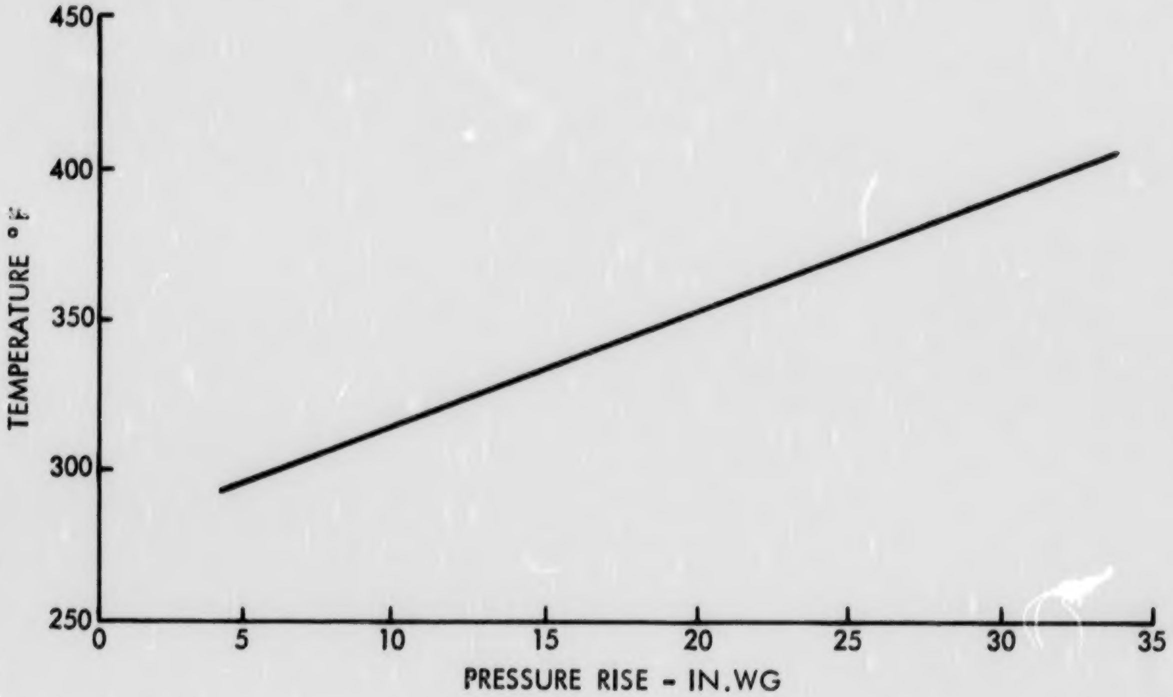

Figure B-5. Mixing section pressure rise for ADTEC scrubber (1 kg H_2O/kg gas)

Table B-1. DATA SUMMARY FOR CHROMASCO PILOT MODEL ADTEC SCRUBBER

Run	Product	System Configuration	Water/Gas	Water Temperature (°F)	Outlet Concentration (g/m^3)	Outlet Concentration (grains/scf)
1	50% FeSi	A	0.97	385	0.046	0.020
2		B	1.4	355	Aborted	Aborted
3		B	1.3	350	0.124	0.054
4		B	1.3	350	0.133	0.058
5		B	0.91	350	0.236	0.103
6		B	0.72	360	0.439	0.192
7		C	0.80	380	0.314	0.137
8		C	1.21	380	Aborted	Aborted
9		C	1.21	360	0.277	0.121
10		C	1.40	350	0.169	0.074
11		C	1.21	370	0.227	0.099
12		C	1.36	350	Aborted	Aborted
13		C			Inlet only	Inlet only
14		C			Inlet only	Inlet only
15		D	0.94	375	0.167	0.073
16		D	0.82	370	0.183	0.080
17		D	0.74	395	0.078	0.034
18		D	0.70	350	0.185	0.081
19		D	0.64	350	0.602	0.263
20		D	0.88	405	0.236	0.103
21		D	0.79	403	0.112	0.049
22	↓	D	0.80	405	0.178	0.078
23	50% FeSi	D	1.24	405	0.114	0.050
24	75% FeSi	D	1.26	400	0.073	0.032
25	↓	D	1.22	400	0.114	0.050

Table B-1. (Concluded)

Run	Product	System Configuration	Water/Gas	Water Temperature (°F)	Outlet Concentration (g/m^3)	Outlet Concentration (grains/scf
26	75% FeSi	D	1.36	340	0.046	0.020
27	↓	D	0.95	400	0.066	0.029
28	↓	D	1.21	375	0.069	0.030
29	75% FeSi	D	1.15	345	0.078	0.034
30	50% FeSi	E	1.13	385	0.378	0.165
31	↓	E	1.16	400	0.286	0.125
32	↓	F	1.07	400	0.192	0.084
33	↓	F	1.07	400	0.201	0.088
34	50% FeSi	F	1.05	400	0.22	0.097
35	CC70	F	1.20	390	0.23	0.102
36	CC70	F	1.13	380	0.03	0.013
37	SiMn	F	1.08	380	0.08	0.036
38	↓	F	1.08	390	0.048	0.021
39	↓	F	1.17	395	0.11	0.048
40	↓	G	1.08	390	0.032	0.014
41	↓	G	1.24	375	0.055	0.024
42	↓	G	1.72	350	0.08	0.035
43	↓	G	1.2	390	0.016	0.007
44	↓	G	2.25	375	0.018	0.008
45	SiMn	G	1.78	400	0.005	0.002

Table B-2. PARTICLE SIZE DISTRIBUTION OF FERRO-SILICON DUST[1/]

	80% Ferro-Silica	50% Ferro-Silica
Finer than 0.1 micron	86.57	89.97
Finer than 0.2 micron	91.32	92.47
Finer than 0.3 micron	97.57	96.63
Finer than 0.5 micron	100.00	100.00

On the basis of currently available information, this system appears to offer significant improvement in the collection of fine particles, at modest energy consumption rates, where a waste gas is available which contains a sufficient amount of thermal energy to heat the water.

Cross-Flow Nucleation Scrubber
Teller Environmental Systems
New York, New York

The cross-flow nucleation scrubber is a vertical packed bed of tellerette packing with water flowing down through the packing. Figure B-6 presents a schematic diagram of the scrubber. The quenched gas passes horizontally through the packed section. The nucleation system removes particulates by a combination of particle growth via condensation, diffusiophoresis, agglomeration, and inertial impaction. Condensation of water occurs preferentially on submicron particles. These particles not only increase in size because of condensation, but collision between particles tends to become less elastic, resulting in acceleration in growth via agglomeration. The diffusiophoretic contribution results from a molecular flow of water molecules toward the cold particle surface. This flow of water, in turn, will sweep the submicron particles toward the cold surface.

The "angle of wetting" and the structure of the particulate are reported to be important factors in the design of each unit.5/ Pilot tests are conducted on each source in order to determine the design factors that must be used. Quenching with water is reported to give better results than does the addition of steam. In some cases a small amount of sonic energy upstream of the tellerette section is used to improve nucleation.5/

The nucleation scrubber has been evaluated on a 15% slip stream from a container glass furnace and on a full-scale basis on a fiberglass furnace.5,6/ Test results for the container glass furnace are presented in Table B-3, while Table B-4 presents the data for the fiberglass furnace. Figure B-7 presents a schematic diagram for the installation at the fiberglass furnace.6/ The source testing methods used to obtain the data reported in Tables B-3 and B-4 are not known. In addition, we were not able to ascertain whether the testing was performed by an independent group or by Teller Environmental Systems. Although the particle size of the emitted particulates was not reported in the above tests, other investigators have established that the emissions from glass furnaces contain very high percentages of submicron particulate.7/

The range of operating conditions for the nucleation scrubber as reported by Dr. Teller are as follows:5/

Pressure drop - 2.5 cm - 10.2 cm H_2O in packing
0 cm - 20.3 cm H_2O in quench section

Water rate - 0.67-5.3 liters/m^3 (5-40 gal/1,000 ft^3) (not including quench)

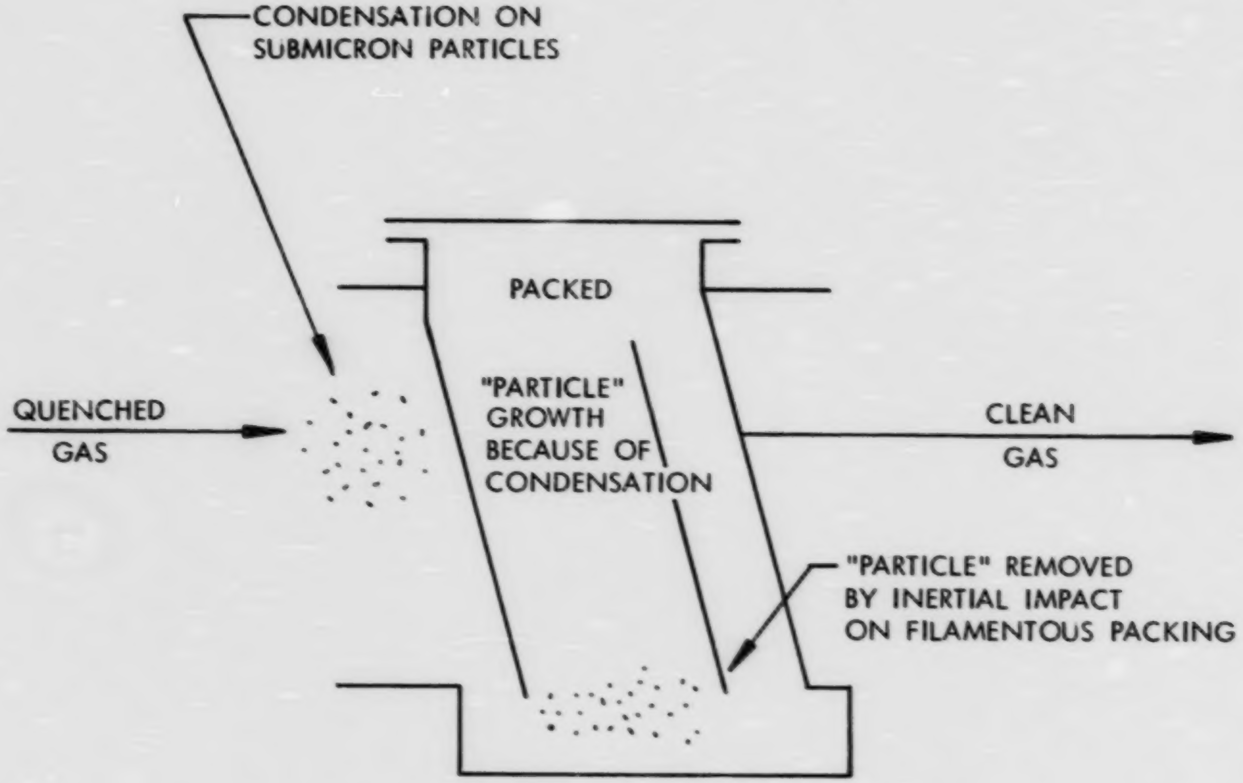
CONDENSATION ON SUBMICRON PARTICLES
QUENCHED GAS
PACKED
"PARTICLE" GROWTH BECAUSE OF CONDENSATION
CLEAN GAS
"PARTICLE" REMOVED BY INERTIAL IMPACT ON FILAMENTOUS PACKING

Figure B-6. Schematic diagram of nucleation scrubber

Table B-3. PERFORMANCE TESTS ON TELLER NUCLEATION SCRUBBER
(Container Glass Furnace)

	Inlet	Outlet
SO_x (ppm)	198	4
Particulate (g/m^3)	0.42	0.07
(grains/scf)	0.18	0.03
Opacity (%)	40	~ 5

System pressure drop: 28 cm of water
Efficiency on Particulates: 83.5%

Table B-4. PERFORMANCE TESTS ON TELLER NUCLEATION SCRUBBER
(Fiberglass Furnace)

	Inlet	Outlet
SO_x (ppm)	65	< 0.3
Gaseous fluoride (ppm)	58	0.3
Particulate (g/m^3)	0.53	0.02
(grains/scf)	0.23	0.01
Boron particulate (g/m^3)	0.06	< 0.001
(grains/scf)	0.025	< 0.0005
Opacity (%)	35	5-10

Exhaust gas flow: 184 m^3/min (6,500 scfm)
Liquid recycle: 1,323 liters/min (350 gpm)
System pressure drop: 10.2 cm (4 in.) of water
Efficiency on particulate: 95.6%

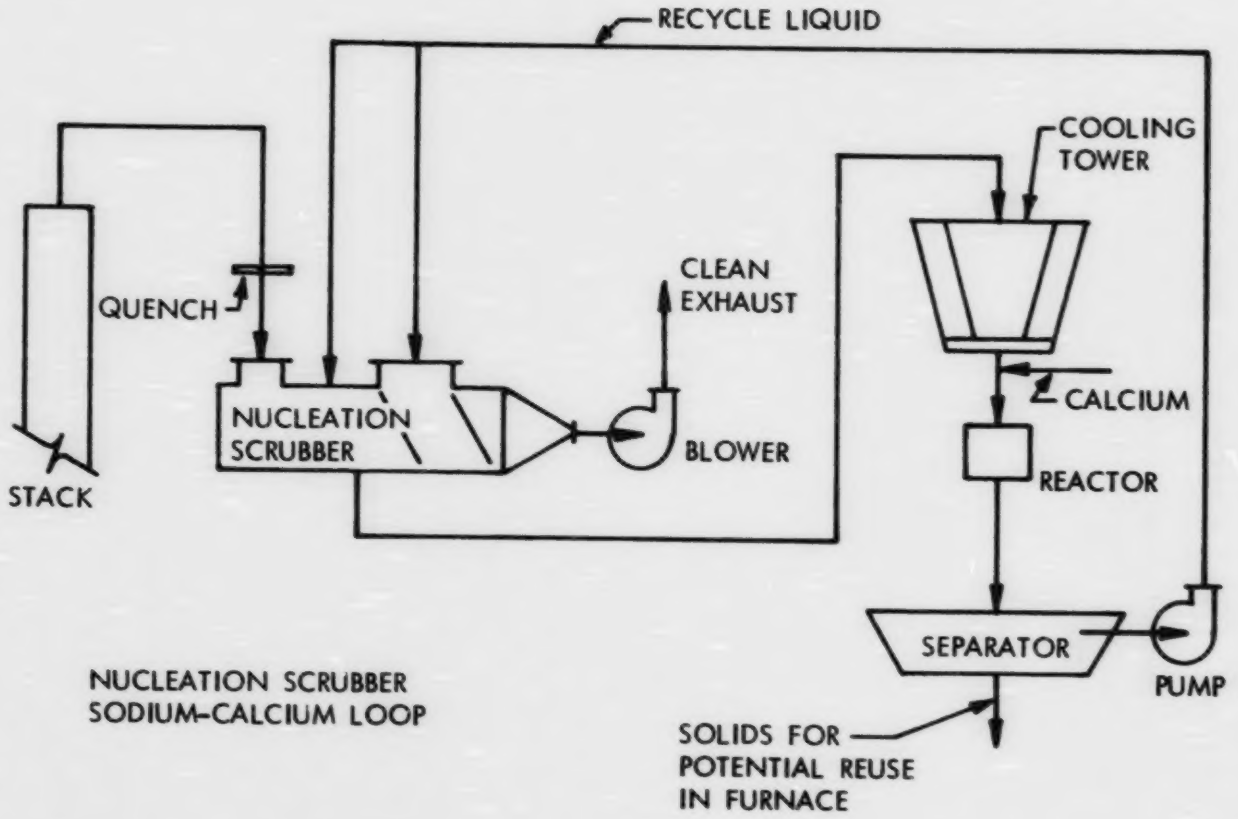

Figure B-7. Schematic diagram of installation of nucleation scrubber systems on fiberglass furnace

Superficial gas velocity - 2.1-2.4 m/sec (7-8 ft/sec)

Cost (FOB) - \$70/m^3/min up to ≈ 85 m^3/min (\$2/cfm up to ≈ 3,000 cfm)
\$1.05-\$1.75/m^3/min for higher cubic meter per minute
(\$0.30-\$0.50/cfm for higher cubic feet per minute)

Available test data do not show particularly high collection efficiency for small particulates, but the device has not been evaluated on a sufficient number of sources to assess its overall performance capability. Testing on a pilot-scale unit using EPA approved methods is recommended.

"Dynactor" Wet Scrubber
R. P. Industries, Inc.
Marlboro, Massachusetts

R. P. Industries has done limited development work on a wet scrubber system that functions like a liquid driven eductor. Figure B-8 is a cross-section view of a single stage "Dynactor."[8/] Liquid entering the system at 40-200 psi is atomized into thin films and droplets of average thickness or diameter less than 1/64 in. (0.04 cm or 400 microns). This liquid discharge diffuses or expands into the reaction chamber causing air or gas to be aspirated by being trapped within the moving shower of films and droplets. The resulting mixed fluid then continues to travel down the reaction column with intimate contact maintained between gas and liquid.

Little if any meaningful test data are available on this system and apparently a small-scale demonstration unit is the only system currently in operation at R. P. Industries. Representatives of R. P. Industries claim that the "Dynactor" has been tested at a plant producing catalyst materials. A "Dynactor" unit operating on the effluent from a cyclone reduced the grain loading from an inlet value of 4.3 g/m^3 (1.89 grain/scf) to an outlet value of 0.02 g/m^3 (0.01 grain/scf)--a collection efficiency of 99.4%. Although the particle size distribution of dust emitted from the cyclone was not measured, it is reasonable to assume that a major portion of the dust was less than 5 microns. Water rates are reported to be about 0.67 liters/m^3 (5 gal/1,000 ft^3).[8/]

The Control Systems Laboratory is currently funding additional testing of this device.

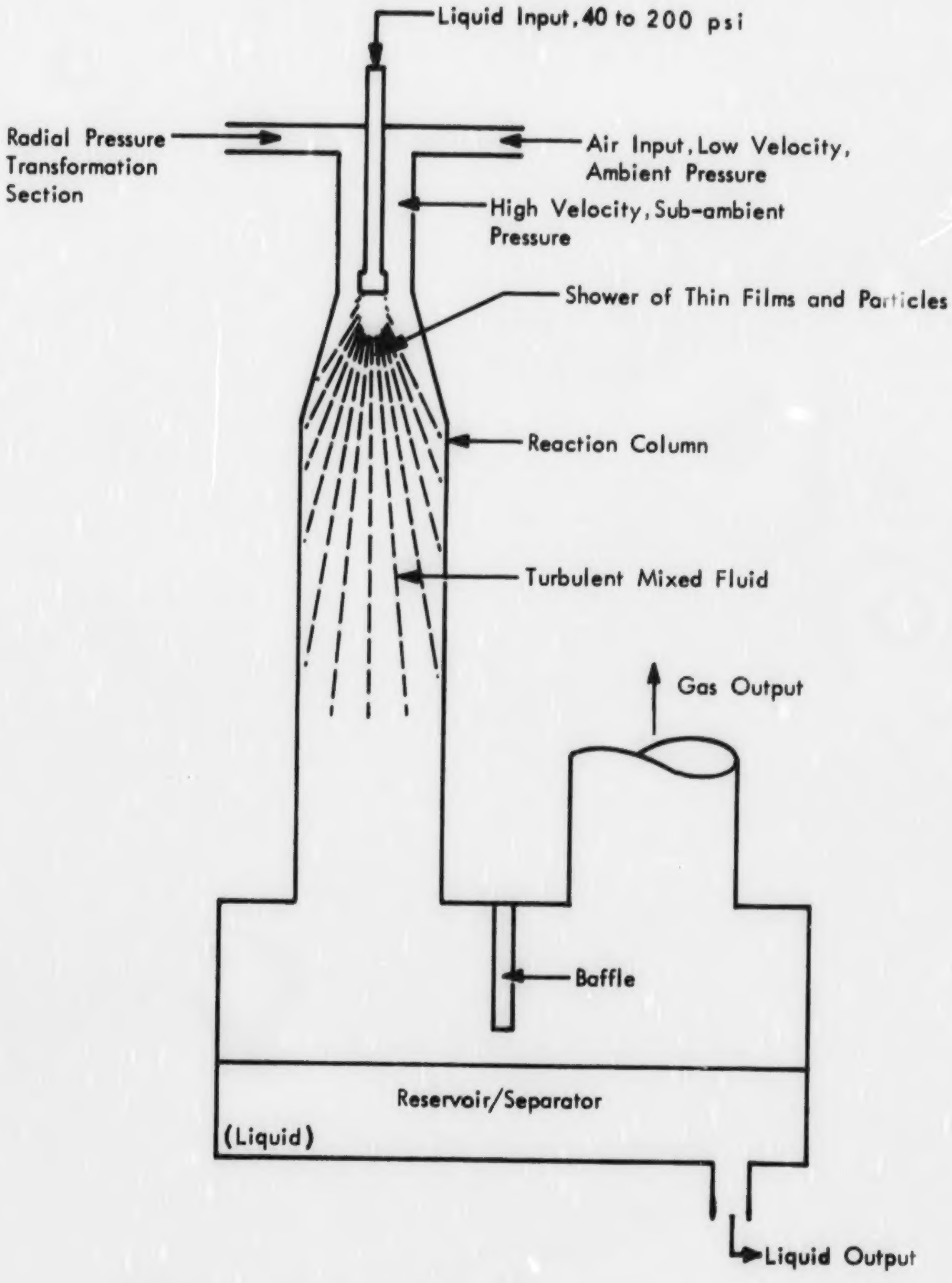
Liquid Input, 40 to 200 psi
Radial Pressure Transformation Section
Air Input, Low Velocity, Ambient Pressure
High Velocity, Sub-ambient Pressure
Shower of Thin Films and Particles
Reaction Column
Turbulent Mixed Fluid
Gas Output
Baffle
Reservoir/Separator
(Liquid)
Liquid Output

Figure B-8. Single-stage dynactor system (cross-sectional view)

Pentapure™ Impinger
Purity Corporation
Elk Grove Village, Illinois

The Purity Corporation, Elk Grove Village, Illinois, has recently announced the development of an air pollution control device which is reported to deliver high efficiency particle removal with low energy requirements.[9]

Figure B-9 is a sketch of the Pentapure™ Impinger. The agglomeration duct has a diameter of 30.5 cm (12 in.) at the entrance and 15.2 cm (6 in.) at the exit. The length of the converging section (agglomeration duct) is about 0.61 m (2 ft) and the distance from the exit of the agglomeration duct to the impingement surface is around 23 cm (9 in.)

As the polluted air stream enters the Pentapure™ Impinger, a differential velocity, which induces particle collision, is produced in the converging section. Submicron particulates will accelerate to a greater degree within the converging section than the larger ones, causing a difference in momentum which may result in collisions and agglomeration between the different size particulates.

To further enhance this particle-on-particle target action, a medium of larger particles can be injected upstream of the converging section. The most common substance is atomized water of controlled droplet size.

Collection of the particulate is achieved when agglomerate clusters impact on the impingement surface. Present models of the Pentapure™ Impinger use either a fixed target or a moving belt onto which a water spray can be directed to further enhance particle entrapment. Reliable test data are not available for this device.

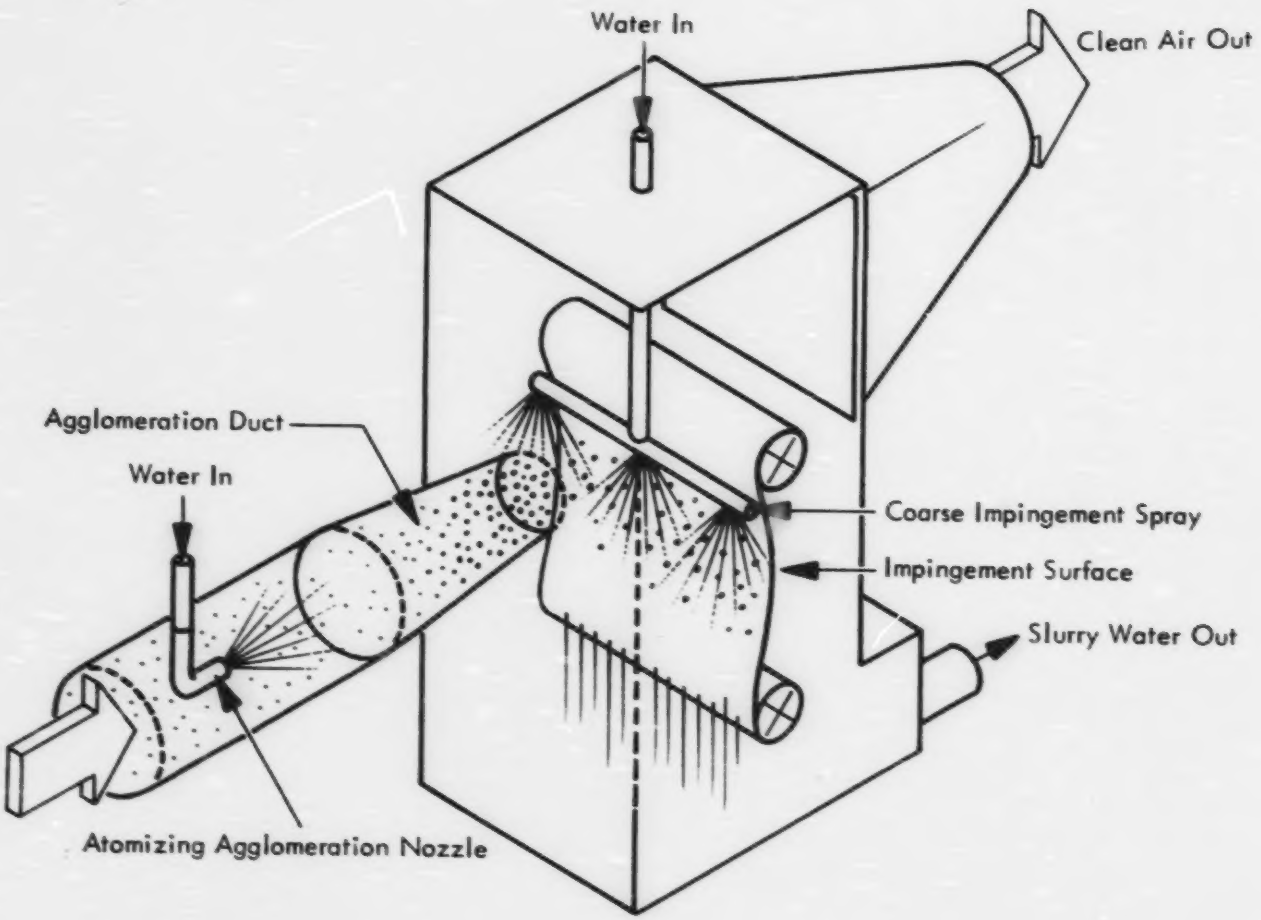

Figure B-9. Schematic diagram of Pentapure™ Impinger

Mystaire™ Scrubber
Heat Systesm--Ultrasonics
Plainview, New York

A scrubbing system involving a wetted-knit mesh filter has recently been developed by Heat Systems--Ultrasonics. Figure B-10 presents a sketch of a laboratory-scale system. As shown in Figure B-10, a short spray chamber preceeds the waterweb filter. Gas and water flow is co-current. A conventional mist eliminator is placed downstream of the waterweb to collect any entrained water drops. Test data are not available on this device.

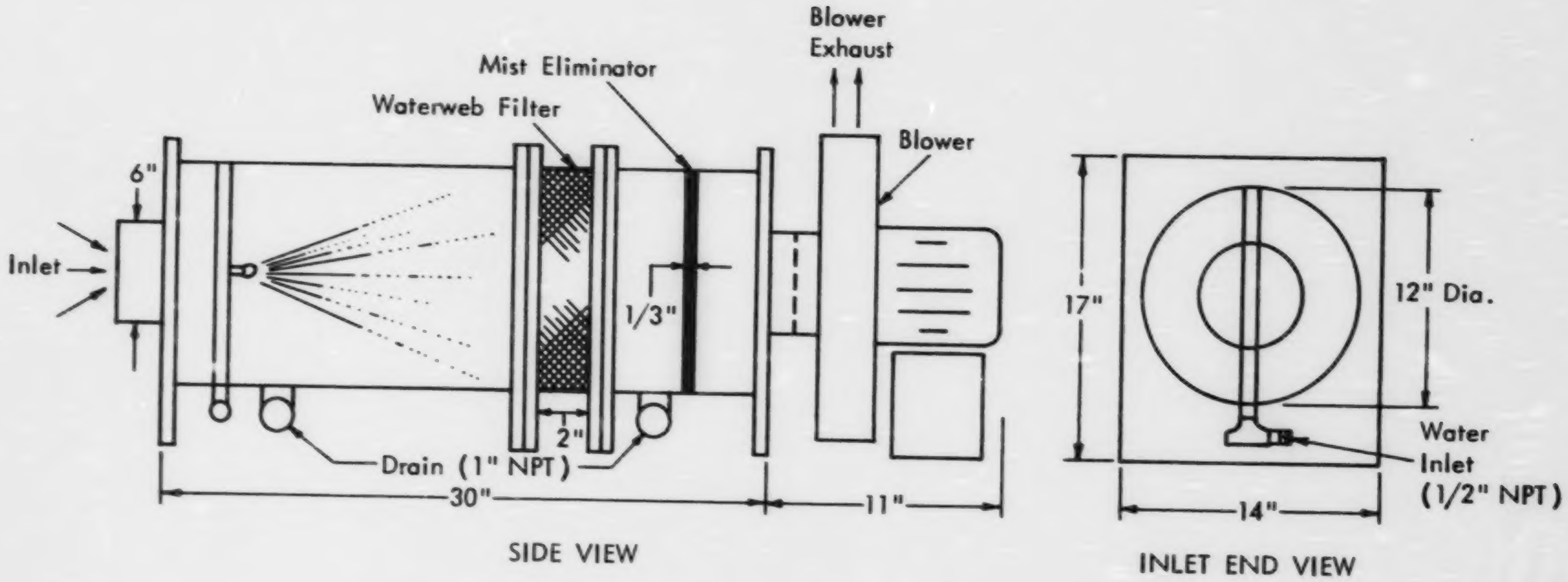

Figure B-10. Schematic diagram of the Mystaire™ laboratory scrubber

Dupont Wet Scrubber System
Dupont Company
Wilmington, Delaware

The Dupont Company has recently announced the development of a wet scrubber system that appears to be nearly the same system as the Mystaire™ Scrubber. Figure B-11 presents a schematic diagram of the Dupont device. As shown in Figure B-11 the gas stream is first sprayed with water and then the gas-liquid mixture is passed through a fiber bed structure having a pore size sufficiently fine and a path length sufficiently long to thoroughly contact the gas stream containing the particulate solids and mist with the liquid.[10]

Tests have been conducted on a laboratory-scale system employing a 10.1 cm (4 in.) diameter knitted fiber bed. Overall bed depths of 10.1 and 20.2 cm were used. Table B-5 summarizes the results of the test runs.[12] Talc dust with the following reported size distribution was used in the tests: 50% < 2.4 microns, 28% < 1 micron, and 14% < 0.5 micron. Methods used to determine the particle size of the talc dust were not reported in Ref. 10. The test results in Table B-5 show quite high collection efficiencies with relatively low pressure drop. Sampling procedures used to obtain the data in Table B-5 were not reported.[10] Titanium dioxide was also used as a test dust with substantially the same results.[10]

Tests were also conducted with different diameter fibers. As shown in Figure B-12, smaller diameter fibers were more efficient on an equal weight per unit volume basis. The packing density was 128 kg/m^3 (8 lb/ft^3) and the void fraction was 0.983 for both beds. The bed material was 304 stainless steel in knitted form. The specific surface area of the 6-mil fiber diameter bed was 459 m^2/m^3 (140 ft^2/ft^3) while that of the 3.5-mil fiber diameter bed was 754 m^2/m^3 (230 ft^2/ft^3). Improved efficiency probably results from a longer path length in the fiber beds composed of smaller diameter fibers.

Reference 12 indicates that the device can operate successfully at scrubbing liquid rates of 0.13-13 $liters/m^3$ (1-100 $gal/1,000\ ft^3$) of gas containing 22.9 g/m^3 (10 grain/scf) of dust. At higher liquid rates, dust loadings in excess of 457.6 g/m^3 (200 grain/scf) were handled.

In order to prevent plugging of the bed, the gas-liquid throughput must exceed the flooding velocity. Figure B-13 presents a generalized plot of the flooding velocity in terms of important system parameters. The flooding velocity is a function of the characteristics of the fiber bed structure, the materials being handled, and the various flow rates.

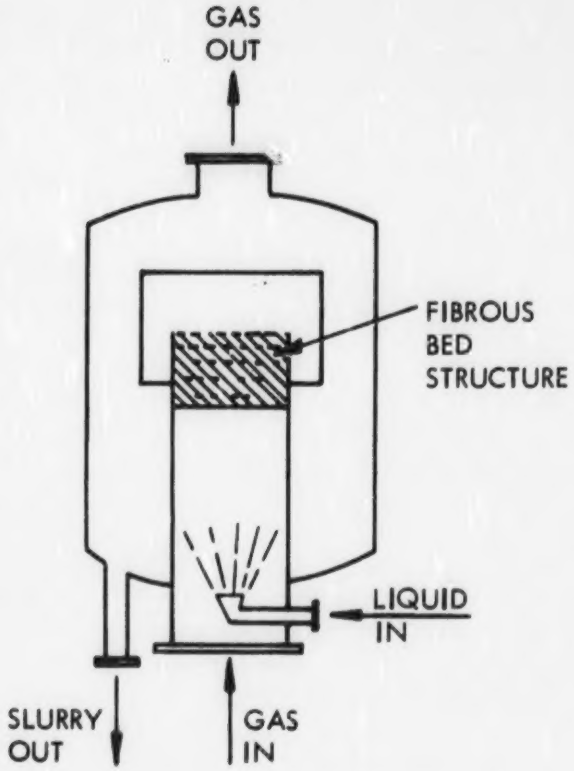

Figure B-11. Schematic diagram of Dupont wetted-fiber bed scrubber[10]

Table B-5. TEST DATA ON DUPONT SCRUBBER

Run	Bed Depth		Bed Density			Liquid Spray Rate		Gas Throughout		Superficial Gas Velocity		Inlet Dust Concentration		Pressure Drop		Collection
No.	(cm)	(in.)	(kg/m^3)	(lb/ft^3)	Bed Material	(liters/min-m^2 of chamber)	(gpm/ft^2 of chamber)	(m^3/min)	(ft^3/min)	(m/sec)	(ft/sec)	(g/m^3)	(grains/ft^3)	(cm H$_2$O)	(in. H$_2$O)	Efficiency
1	10.2	4	64.1	4	Bed	896	22	5.04	178	10.4	34	30	13	28.7	11.3	98.9
2	10.2	4			composed			5.89	208	12.2	40	32	14	34.8	13.7	98.7
3	10.2	4			of			1.30	46	2.7	9	11	5	7.4	2.9	97.7
4	10.2	4			16 mil			1.84	65	3.7	12	25	11	8.6	3.4	98.4
5	10.2	4			diameter			2.27	80	4.9	16	37	16	11.4	4.5	99.2
6	10.2	4			knitted	977	24	1.36	48	2.7	9	64	28	10.9	4.3	99.8
7	10.2	4			polyethylene			2.66	94	5.5	18	43	19	20.6	8.1	98.8
8	10.2	4						5.04	178	10.1	33	32	14	33.5	13.2	98.9
9	20.3	8						1.36	48	2.7	9	149	65	22.9	9.0	99.4
10	20.3	8						2.61	92	5.5	18	110	48	48.3	19.0	99.6
11	10.2	4	320.4	20	304 stainless steel	407	10	3.71	131	2.7	9	85	37	9.4	3.7	98.8
12	10.2	4			16-mil diameter			5.10	180	3.7	12	85	37	12.2	4.8	98.5
13	10.2	4	640.7	40	304 stainless	407	10	4.11	145	3.0	10	64	28	24.4	9.6	98.6
14	10.2	4			11-mil			5.01	177	3.7	12	82	36	25.1	9.9	98.9
15	10.2	4	192.2	12	diameter	407	10	3.88	137	2.7	9	50	22	27.2	10.7	99.4
16	10.2	4						4.96	175	3.7	12	62	27	26.2	10.3	98.7

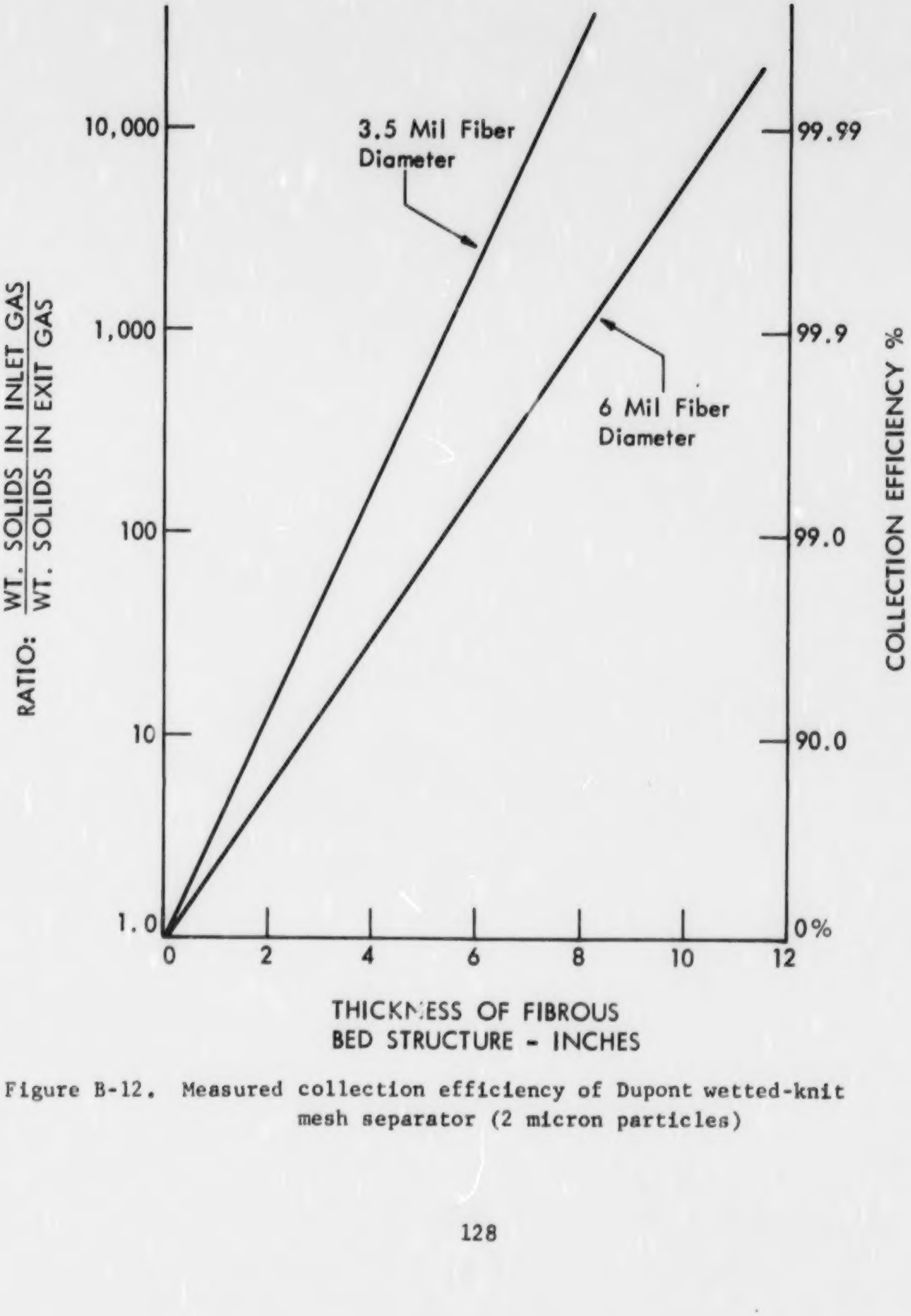

Figure B-12. Measured collection efficiency of Dupont wetted-knit mesh separator (2 micron particles)

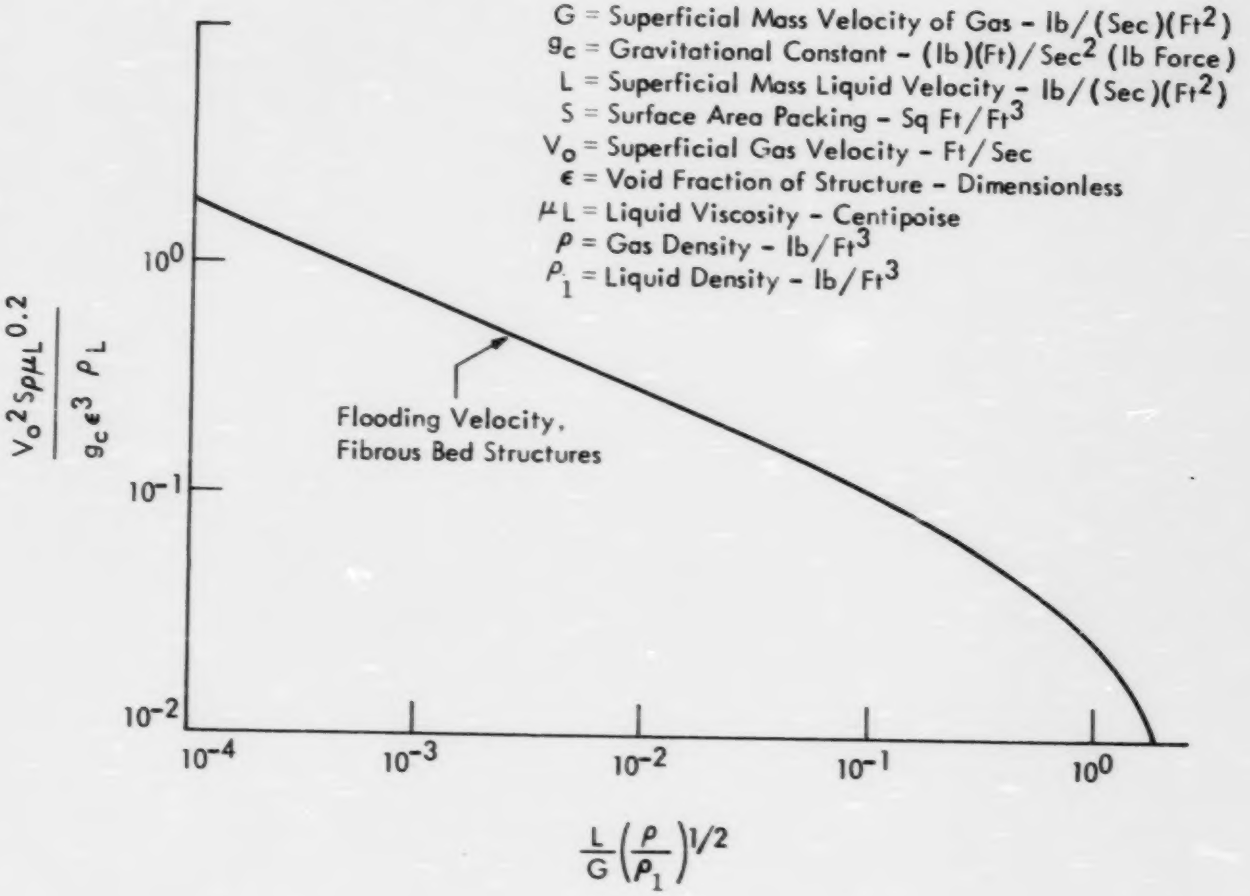

Figure B-13. Correlation of flooding velocity of Dupont scrubber

The Dupont scrubber system appears to be very similar to the Mystaire™ unit and additional testing with EPA approved methods is warranted.

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APPENDIX C

CONDENSATION SCRUBBING FOR PARTICULATE COLLECTION

INTRODUCTION

The collection of submicron particulates from various gas streams can be enhanced by the use of condensation effects. Over a period of years, there have been many references to the use of scrubbing systems in which condensation effects have occurred. In most of the early literature, there appeared to be no deliberate attempt to optimize the effects of condensation phenomena. Available theoretical and experimental information on condensation scrubbing is summarized in the following sections. Specifically, the following sections present: (1) theoretical studies of condensation phenomena; (2) experimental studies of particle conditioning by steam and condensation scrubbers; (3) estimates of costs of condensation scrubbers; and (4) areas and/or methods of potential application of steam condensation.

THEORETICAL ASPECTS OF CONDENSATION SCRUBBING

Condensation scrubbing involves particle removal from the gas stream via the use of a temperature gradient, a vapor concentration gradient, vapor condensation, or combinations of the three. It is not necessary that all forces act simultaneously, but in most actual cases they do.

Forces which cause particle motion may result from momentum differences imparted to the particle on opposite sides by the molecules colliding with it or desorbing from it. In the case of a temperature gradient, hotter (and thus faster) molecules colliding with the particle will impart a higher momentum to the particle than the cooler (slower) molecules. Aerosol particles will then drift in the thermal gradient toward the cold surface. Particle movement by this mechanism is called thermophoresis.

In a concentration gradient, which is accompanied by diffusion but not necessarily by net motion of the gas phase, the heavier molecules will impart a higher momentum than the lighter molecules. If there is a net motion of the gas phase (Stefan flow), additional force is applied to the particles. The combination of forces due to Stefan flow and the molecular weight or concentration gradient is referred to as the diffusiophoretic force and particle motion as diffusiophoresis.

Mass transfer, which causes the diffusiophoretic force, can be caused by evaporation, condensation or a chemical reaction. Particulate collection via thermophoresis and/or diffusiophoresis is most often considered in conjunction with the use of water as a scrubbing media; i.e., wet scrubbers. In the case of condensation of water vapor, the Stefan flow force acts towards the condensing surface while the molecular weight gradient force acts away from it. The net force is toward the cold surface.

Particle growth resulting from the condensation of vapor on particles may occur. An advantage of particle growth would be improved particle collection by inertial impaction.

The individual mechanisms or forces which may be acting in condensation scrubbing have been studied in considerable detail from a theoretical standpoint. Theoretical models for thermophoresis and diffusiophoresis have been advanced by several investigators1-9/ (also see Appendix A).

Nucleation and condensation processes have been studied in some detail. Water vapor may self nucleate and condense into drops in the absence of condensation nuclei if the degree of supersaturation is great enough. At lower supersaturations, however, a nucleating surface is necessary for condensation. The conditions necessary for condensation to occur on a surface are determined by applying equilibrium thermodynamics.39/ A system is in stable (unstable) equilibrium at constant temperature when the Helmholtz free energy is minimized (maximized). This fact is used to find the equilibrium saturation ratio for a surface exposed to the vapor. (The saturation ratio is the ratio of the vapor pressure at the point in question to that of a plane water surface.) If, then, the saturation is greater than required for equilibrium, condensation occurs and will continue until equilibrium is again attained.

If an insoluble surface is present, drops of the critical radius will form on this surface at a higher rate than they will self nucleate. This is due to the fact that they have less volume and require fewer molecules than for the case of homogeneous nucleation; hence the free energy increase is smaller. Their volume is smaller because they can form as a partial sphere resting on the surface rather than the complete sphere necessary in the absence of the surface.

If the particle is soluble, nucleation will occur even more readily. Raoult's law states that the equilibrium vapor pressure over a solution is less than that over pure water by a factor equal to the mole fraction of water in the solution.

After a drop of critical size has been nucleated, it grows at a rate determined by the ambient environment and the conditions at its surface, just as the condensation flux to a flat wall depends on these boundary conditions. References 40-43 discuss nucleation, condensation, and particle growth in detail.

Theoretical aspects of condensation scrubbing have also been investigated to some extent. Hales and his associates at Battelle Northwest have explored the possibilities of aerosol removal in an enclosed environment at a condensing stream boundary.[10-12] These studies were concerned with a nuclear reactor accident and their analyses were confined to liquid sheets with only natural convection as the air moving mechanism.

Sparks and Pilat[13] published an analysis of a spray column with condensation taking place on the drops. Their analysis indicates that for the case of Stokes Number equal to 0.6, the collection efficiency in a spray column, where the vapor pressure gradient is 10^5 mbar/cm, was 100% as compared to an efficiency of 0% with no vapor gradient present.

The most comprehensive analysis of condensation scrubbing has been performed by Calvert and his associates under contract to the Environmental Protection Agency.[14-16]* The objective of the research reported in Ref. 16 was to determine the feasibility of using condensation scrubbing for fine particulate collection. Models have been developed for the prediction of particle collection in scrubbers of several representative types.

Models for plate scrubbers (as represented by sieve plates) and packed scrubbers have been developed to the point where they appear to predict with acceptable accuracy the simultaneous effects of heat and mass transfer for gas/particles and gas/liquid diffusiophoresis, thermophoresis, Brownian diffusion, inertial impaction, and changes in particle concentration, humidity, and temperature as the gas flows through the scrubber.[16]

The model for spray scrubbers required appreciable effort on the computation of particle trajectories for the combined effects of flux forces (i.e., thermophoresis and diffusiophoresis) and inertial collection by liquid drops was found to be defined by a new dimensionless parameter which is the ratio of flux force deposition velocity to the gas velocity. This ratio was called the "flux deposition number." If the flux deposition number is greater than 0.1, particle collection efficiency will be good and if it is less than 0.01, efficiency will be poor. The model for collection from an impinging jet showed that negligible benefit is given by flux force deposition because of the very short contact time.[16]

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* Research is supported by the Control Systems Laboratory

Theoretical analysis showed that, in general, the particle deposition velocity has to be on the order of 0.1 cm/sec (0.04 in/sec) or larger for appreciable collection efficiency to occur. Diffusiophoresis can produce deposition velocities this high under the heat and mass transfer conditions of a realistic scrubber, but thermophoresis generally cannot. If particle growth due to condensation occurs, inertial impaction of the resulting 2 or 3 micron diameter particles can give sufficiently high deposition velocities. Particle growth has the advantage that the high deposition velocity can persist after the heat and mass fluxes are dissipated, because once the particles are enlarged, they can be collected to an increasing degree at the cost of relatively little additional pressure drop.[16]

EXPERIMENTAL STUDIES OF CONDENSATION SCRUBBING

Experimental studies related to condensation scrubbing have been performed on individual mechanisms (i.e., thermophoresis, diffusiophoresis, and particle growth) and on entire scrubber systems. Experimental studies of thermophoresis are presented in Refs. 5 and 17-20. The results of experimental work on diffusiophoresis are presented in Refs. 21-23.

Experimental investigations on steam condensation related to particulate removal from gas streams has been focused on two areas: (1) particle conditioning by steam condensation, and (2) performance of condensation scrubbers. Very little systematic work has been done in either area.

Table C-1 presents a summary of the pertinent previous experimental work conducted on particle conditioning by steam and on condensation scrubbing. The particle conditioning experiments demonstrate that buildup of particles (i.e., increase in particle size) by condensing steam can be achieved. However, with the exception of the work of Prakash and Murray, particle loadings used in the experimental work were very low and highly unrealistic for most industrial situations. Steam usage rates up to 1.0 kg/m^3 (62.5 lb/1,000 ft^3) of gas were used in the particle conditioning experiments summarized in Table C-1. The amount of steam condensed was reported only by Prakash and Murray.

Table C-1. SUMMARY OF SELECTED EXPERIMENTAL INVESTIGATIONS OF STEAM CONDENSATION

Investigator	Condensation Device	Test Conditions	Parameters Studied	Secondary Aerosol Collection System	System Performance	Comments
I. Particle Conditioning						
a. Fahnoe et al.[24]	5.1 cm dia. standard stainless steel pipe	Aerosol: NaCl, silver iodide Aerosol particle size: a) NaCl-0.80-1.2 μm b) Silver iodide-maximum size 0.8 μm Aerosol grain loading: a) 0.001-0.002 g/m^3 b) 0.0007 g/m^3 (silver iodide) Steam injection rate: 0.16 kg/m^3 of air Steam condensation rate: estimated at 0.01 kg/m^3 of air Inlet air temperature: 70-90°F Relative humidity of inlet gas: < 20%	Aerosol type, aerosol particle size	a. Cyclone b. Peabody scrubber	Condensation system: 99% buildup of aerosol to particles > 2 μm with NaCl, but only 71% buildup with silver iodide. Secondary collection system: a) Cyclone collected 94.3% of particles ≥ 2 μm b) Peabody scrubber collected 90.5% of particles ≥ 2 μm	Very low grain loading and soluble particulates tend to minimize quantity of steam required. Grain loading not realistic of industrial conditions. Difference in the extent of particle buildup is apparently due to different type of particle and smaller size of the silver iodide aerosol.
b. Goldsmith and May[25]	5 cm dia., 50 cm long, water-cooled glass tube	Aerosol: oxide particles Aerosol particle size: 0.05-0.5 μm Steam injection rate: 0-1 kg/m^3 of gas	Gas velocity	No secondary collection system. However, elbow at exit of condenser provided impaction surface	Up to 98% removal of aerosol	Removal efficiency varied with velocity of aerosol through the tube. This effect is probably due to the elbow at the exit of condenser, i.e., inertial impaction plays an important part in the system.

Table C-1. (Continued)

Investigator	Condensation Device	Test Conditions	Parameters Studied	Secondary Aerosol Collection System	System Performance	Comments
c. Davis[26,27]	Vertical 10.2-cm dia. glass pipe, water-cooled condenser	Aerosol: Nine particle substances were tested, including examples of hydrophobic, hydrophilic and hygroscopic particles. These aerosols were tested over a particle concentration range of 10^2 to 2×10^6 particles/cm^3 and over a particle size range of 0.01 to 2.7 µm in dia. Steam injection rate: 0-0.72 kg/m^3 of air	Aerosol type, aerosol particle size, aerosol grain loading	No secondary collection system on condenser	Extent of particle removal varied with particle size. Removal of particles as a function of aerosol type varied as follows: a. Hydrophobic particles: up to 90% depending on initial particle concentration b. Hydrophillic particles: up to 98% depending on initial particle concentration c. Hygroscopic particles: in excess of 99%	Low grain loadings tend to minimize quantity of steam required.
d. Prakash and Murray[28]	Variable length glass pipe of 2.5 cm I.D. steam injected through a simple nozzle into test section	Aerosol: $CaCO_3$, ZnO, Na_2O_4, and Na_2CO_3 Aerosol particle size: See Figure C-1 Aerosol grain loading: 0.7-7.0 g/m^3 Steam injection rate: 0.03-0.1 kg/m^3 Steam condensation rate: 0.01-0.03 kg/m^3 Gas flow rate: 0.13 m^3/min	Aerosol type, aerosol particle size, aerosol grain loading	No secondary collection system	Particle growth was found to depend upon particle size, particle type, and particle grain loading in some cases. Particles soluble in water or easy to wet showed higher growth rates. For these aerosols, particle growth was not affected by particle loading or by the size of the particles within the range studied. Growth rate for particles insoluble in water is strongly dependent upon particle loading and particle size. Condensation was favored on larger particles and by higher loadings.	Results of program indicate that particle conditioning by steam condensation can be of considerable value in improving efficiencies of gas cleaning equipment. Steam usage rates are among lowest reported in literature.

Table C-1. (Continued)

Investigator	Condensation Device	Test Conditions	Parameters Studied	Secondary Aerosol Collection System	System Performance	Comments
II. Condensation Scrubbing						
a. Lohs[29]	Steam tower	Aerosol: Suspension A: Sodium sulfate (soluble in H_2O), particle size 0.3-2.0 µm Suspension B: Polystyrene (hydrophobic dust), particle size 0.3-2.0 µm Steam injection rate: 0.5-0.6 kg/hr	Aerosol type	Spray tower with water rates ranging from 0.25-1.0 liter/min	Suspension A: 97% removal at 0.5 µm with 3.3 lb steam/hr Suspension B: 80% removal at 0.5 µm with 1.5 kg steam/hr	Separation efficiency of spray tower was enhanced by addition of steam. Improvement of up to 70% was observed. Major improvement occurred in 0.3-0.5 µm particle size range.
b. Schauer[30]	Convergent-divergent nozzles	Aerosol: DOP Aerosol grain loading: 0.27 g/m^3 Gas flow rate: 0.28-0.42 m^3/min Steam injection rate: 3.2 kg/m^3	Nozzle configuration Double convergent-divergent nozzle system is necessary to get good condenation	Pease-anthony cyclonic scrubber	Efficiencies on the order of 99.9% were obtained on 0.3 µm particles	Very low grain loading used in these experiments tends to minimize quantity of steam required. However, the use of a hydrophobic dust probably compensates.
c. Lancaster[31]	Rectangular duct	Aerosol: zinc oxide Aerosol particle size: ~ 1 µm Aerosol grain loading: 0.23-11.4 g/m^3 Steam injection rate: 0.02-0.18 kg/m^3	Residence time	Cyclone	Up to 95% removed at grain loadings of 11.4 g/m^3. Up to 85% removal at grain loading of 0.23 g/m^3	Inefficient use was made of available steam because the condensable fraction of the injected steam was condensed on a small percentage of the total particles in the system.

Table C-1. (Concluded)

Investigator	Condensation Device	Test Conditions	Parameters Studied	Secondary Aerosol Collection System	System Performance	Comments
d. Rozen and Kostin[32]/	Perforated plate column with alternate hot and cold plates	Aerosol: Oil mist Aerosol particle size: ~ 0.3 µm	Plate temperature, and number of pairs of hot and cold plates	None	Up to 90% removal on fourth pair of plates for a temperature difference of 50°C between hot and cold plates	Experimental data could be correlated by equation of form $P = 12.5\ q^{-0.56}$ where P = particle penetration and q = mass of steam condensed per gram of inlet particles
e. Litvinov[33-36]/						
	Venturi Scrubber	Aerosol: Carbon black and Apatite Aerosol particle size: Carbon black ~ 1 µm, Apatite ~ 1.7 µm		Two stage sieve column	Collection efficiency increased under conditions favoring condensation	
f. Terebenin and Bykov[37]/	Wetted wall rectangular ducts	Aerosol: Tin fume Aerosol particle size: ~ 0.1 µm		None		Particle collection attributed to growth by condensation and sedimentation of particles by diffusiophoretic force.

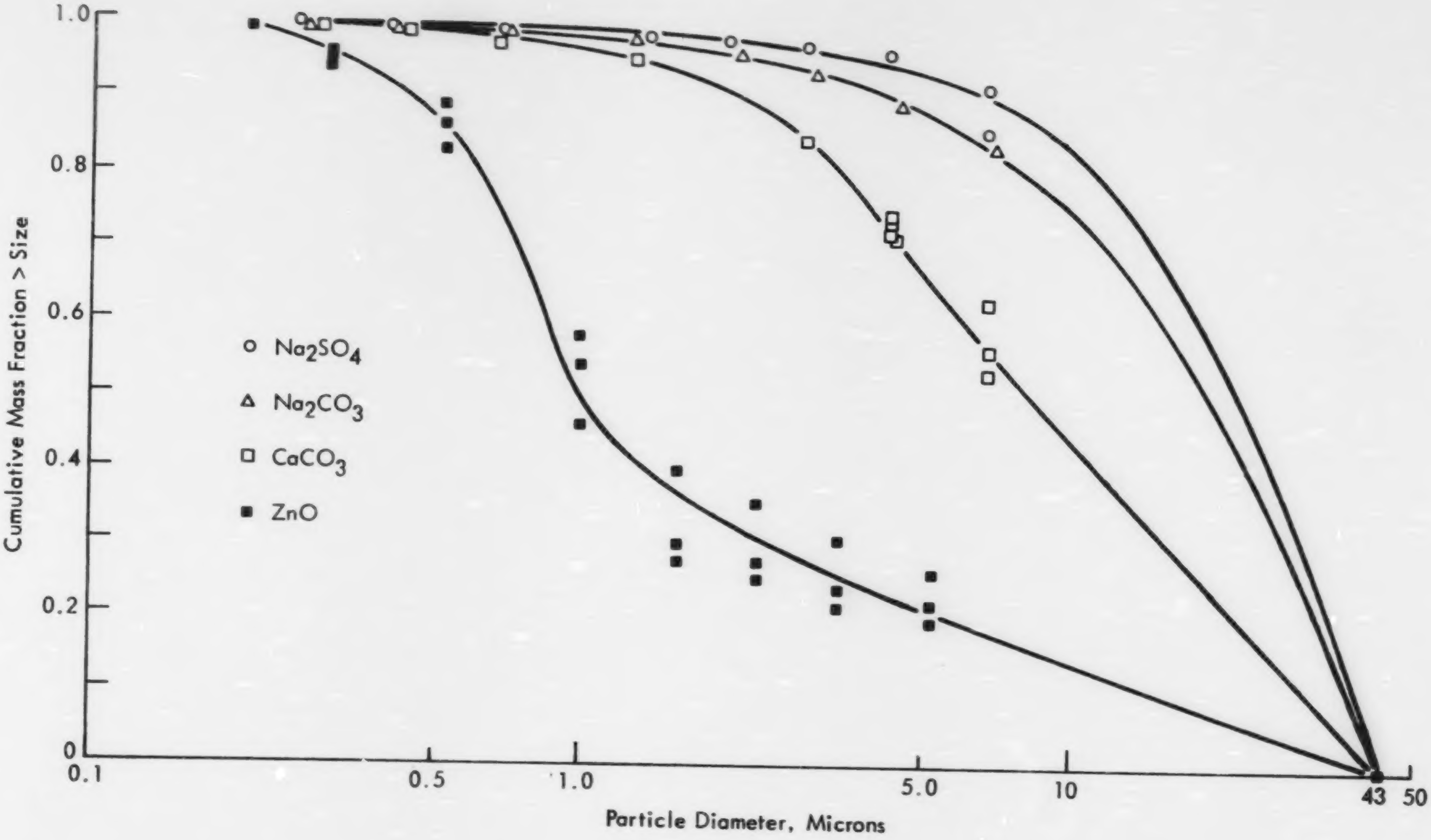

Figure C-1. Cumulative mass fraction distribution of experimental aerosols used by Prakash and Murray (see Table C-1 for summary of work)

Prakash and Murray reported that within the range of their experiments, the amount of steam condensed was found to be proportional to the amount of steam injected--approximately 33% of the steam condensed. The portion of the steam condensed on the particles was not reported, but it was assumed to be proportional to the total quantity of steam condensed in the system.

The main conclusions from the particle conditioning experiments are:

1. Growth of particles is dependent upon type of aerosol.

2. Dependence of particle growth on particle size and grain loading varies with type of particle.

3. Particles soluble in water or easy to wet were not strongly affected by particle loading or particle size and exhibited higher growth rates.

4. Growth rate of particles insoluble in water is strongly dependent upon particle loading and particle size. Condensation increased in gas streams containing larger particles and higher grain loadings.

5. Particle conditioning by steam condensation can be of considerable value in improving the efficiencies of gas cleaning equipment.

Experimental work on condensation effects in scrubbers is currently being conducted at Stanford Research Institute and at A.P.T., Inc., under contracts from EPA.* Previous work by SRI investigators has shown that less power input is required for the same efficiency when gases are cooled below the dew point. The current work at SRI involves an investigation of the reduction in power input that can be realized in venturi or orifice type scrubbers by taking advantage of condensation effects. The purpose of the work is to compare efficiency results at fixed power inputs (ΔP), with and without condensation.

Experimental work at A.P.T., Inc., is directed to the study of plate-type scrubbers. Theoretical work by A.P.T., Inc., had indicated that plate-type scrubbers should be good for condensation scrubbers on the basis of their assumed heat and mass transfer characteristics. Initial studies have been performed with a single sieve-plate column.16/ The test section consisted of a 10.2 cm diameter glass column and the sieve plate was made out of 1.6 mm aluminum sheet and had an overall diameter of 10.2 cm. The plate had 30 perforations of 4.8 mm diameter, adding up to 6.6% free area on the plate. Two straight weirs, 8.1 cm long and 9.5 mm high were provided for liquid inlet and outlet on the plate. The results of a limited number of tests indicate that diffusiophoresis is the major contributor to particle collection for a single plate.

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* Work at both locations is being funded by the Control Systems Laboratory.

Future experimental work at A.P.T., Inc., will focus on multiple plate columns. Multiple plate columns should provide staging effects which permit better utilization of condensation effects.38/

The possibility of using multiple plate columns in conjunction with steam injection was discussed by Bralove.44-46/ Bralove discusses the adaptation of a Peabody perforated plate scrubber for steam injection (see Figure C-2).44-46/ With the single steam injection stage before the scrubber as shown in Figure C-2, the action of the five plates would be to remove the particles which were of the greatest size on the first plate, with the efficiency of each plate rapidly diminishing. The overall efficiency of removal would not be significantly higher than the efficiency with which the particles were preferentially wet.

Bralove suggests that the overall efficiency could be improved by increasing the number of steam-injected stages by introducing points of injection between each plate. This would serve to wet the particles which were not wet by the previous stage, this injection occurring after the wetted particles were removed. Interstage cooling would be necessary for condensation to take place in the next stage.

Figure C-3 shows Bralove's projected application of a typical plate scrubber employing five stages of steam injection. Steam is injected through ring injectors into the gas stream before it enters each of the plates. The dust-laden gases pass through the orifices in the plates located directly above. The gases are then passed through an interstage cooler. While primary cooling occurs on the plate itself, additional cooling is necessary to effect efficient condensation in the succeeding stage. Instead of an interstage cooler, an additional scrubber plate designed specially for cooling might be used. Based on limited experimental data for radioactive dusts, Bralove estimated 85-90% cleanup per stage employing steam injection and an overall efficiency exceeding 99.99%.

Bralove also discusses sudden cooling to effect condensation of water about dust contained in a hot saturated gas.46/ A plate scrubber was suggested by Bralove as being suitable for particle collection by sudden cooling.46/

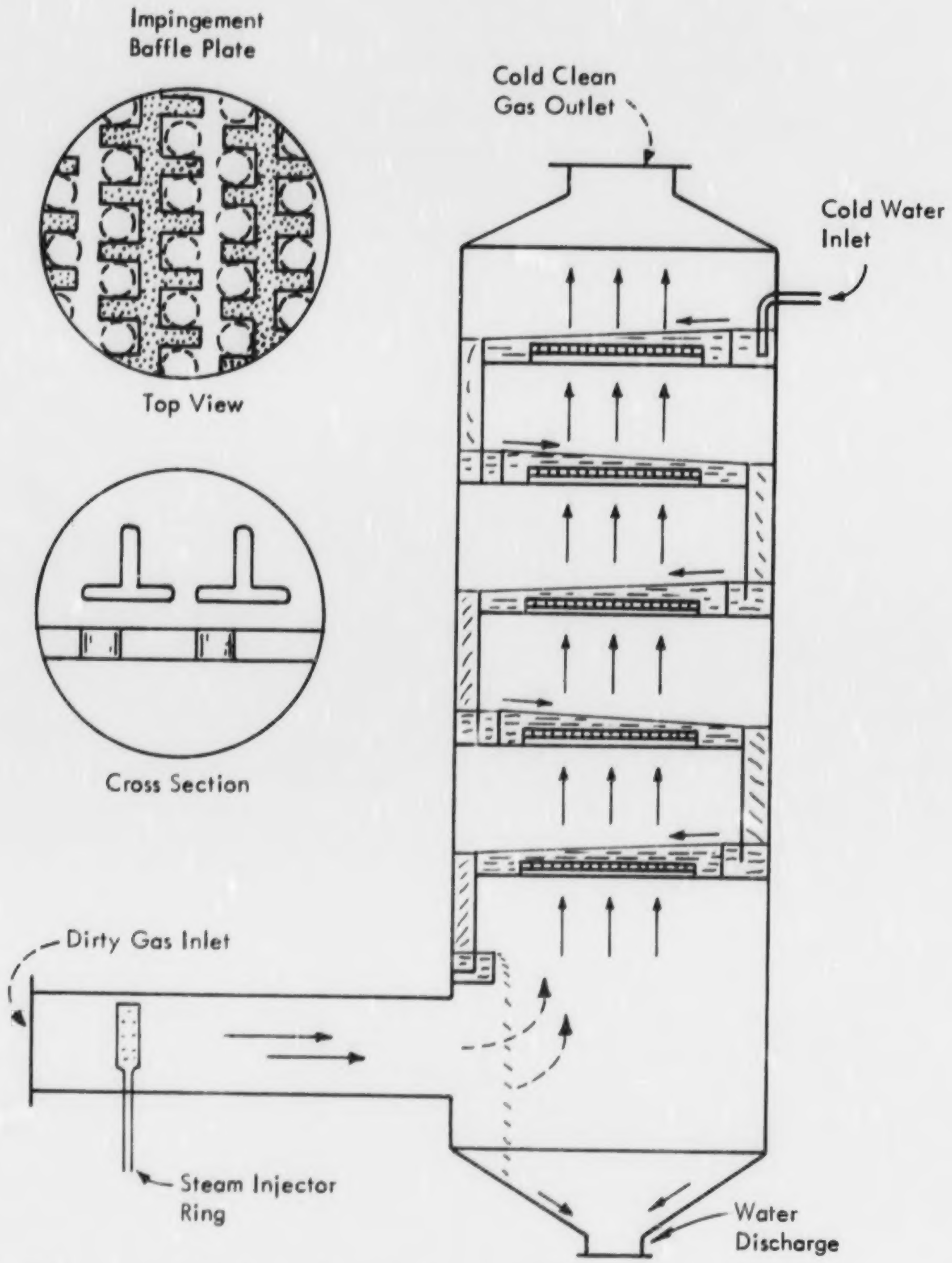

Figure C-2. Five-stage Peabody perforated plate scrubber adapted for steam injection

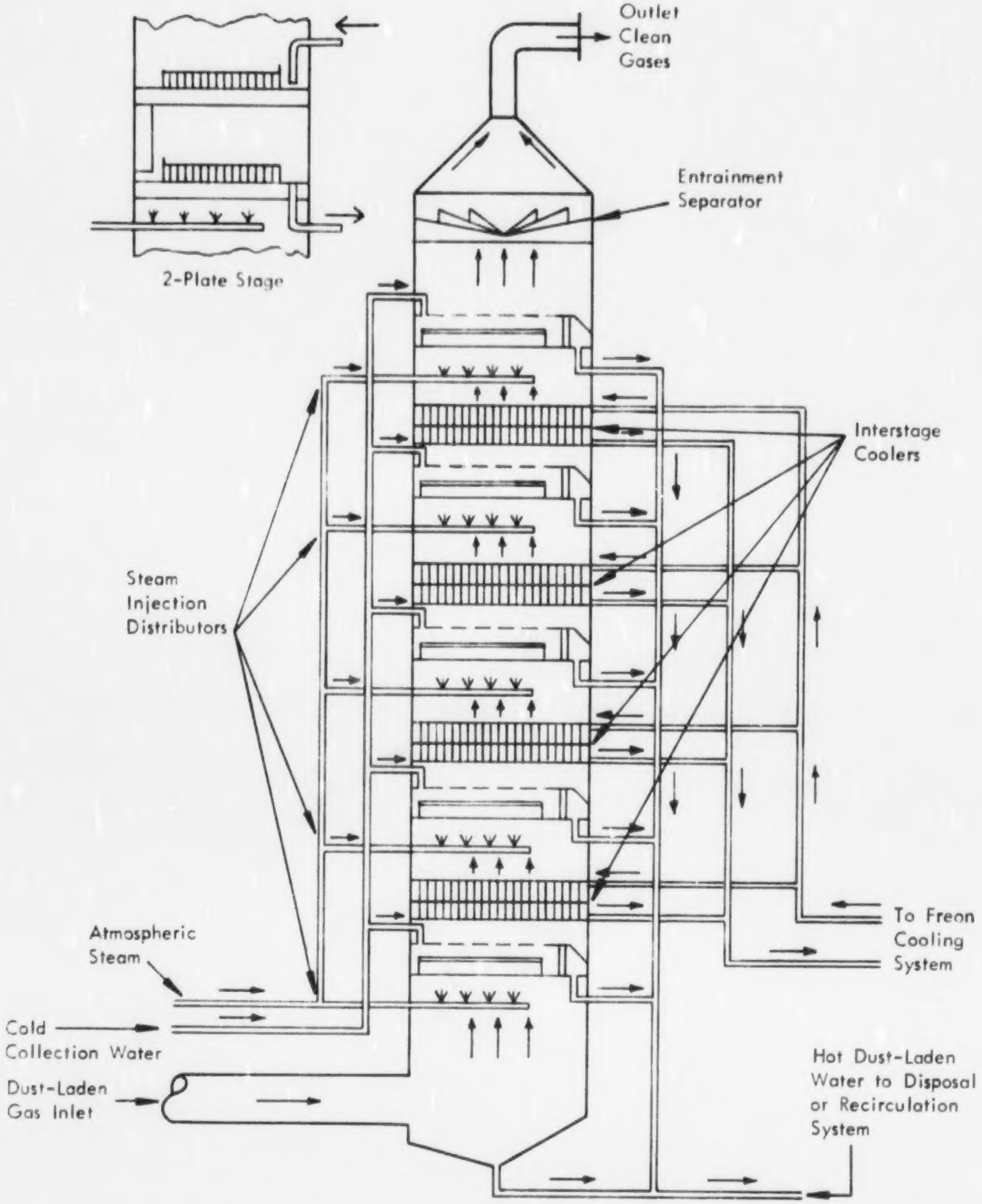

Figure C-3. Five-stage steam injection plate scrubber

Some of the major observations from previous experimental studies are:

1. Collection efficiency depends heavily on the amount of water vapor condensed per unit mass of dry gas.

2. Collection efficiency also depends significantly on particle concentration. There is a trend of efficiency increasing as particle number concentration decreases.

3. Effectiveness of condensation scrubbing depends upon the type of dust being scrubbed. Efficiency varies in the following order: hygroscopic dust > hydrophilic dust > hydrophobic dust.

4. Mechanism of particle growth via condensation is dependent upon type of particle. The difference in the growth mechanisms probably accounts for some of the variations noted in scrubbing efficiency.

5. The effects of scrubber design include the following:

a. Multiple-stage or continuous contact type equipment is superior to single-stage condensation because it provides more opportunity for the collection of particles after they have grown.

b. Distribution of the condensation over several stages is preferable because of the enhanced growth which can occur after the particle concentration has been reduced.

ECONOMICS OF CONDENSATION SCRUBBING

The economics of condensation scrubbing are expected to be dependent upon the source and the characteristics of the emitted particulates. Costs for condensation scrubbing will be highly dependent on the amount of steam which is condensed, especially if steam or fuel to evaporate water must be purchased. Cooling water may also be required to condense the steam and the amount of cooling water needed will depend on the temperature rise of the water in the scrubbing system. The efficiency of collection as noted in the preceding section varies with particle type and grain loading. As a result, the cost to achieve a specific degree of control will vary with those parameters.

A general economic analysis of condensation scrubbing has been performed by Calvert, et al.[16,38] The main conclusions from the analysis were:

1. The most favorable situation occurs when the enthalpy of vaporization is available from the gas to be cleaned.

2. The purchase of steam might be justified when high efficiency collection of fine particles is required.

3. Cooling water costs can be significant depending upon the system.

CONCLUSIONS

The work on condensation scrubbing which has been conducted to date indicates it may be an important avenue to exploit in order to collect fine particulates. Two avenues appear most feasible: (a) injection of steam into a cold dust-laden gas; and (b) sudden cooling of a hot and humid gas. Sudden cooling is an inefficient method for producing condensation since most of the water condenses on the cooling surface, but enough may condense on particles to affect particle collection. A gas above 120°F cannot be treated very effectively by steam injection because condensation will not be significant.

Available theoretical and experimental data suggest that multiple stage or continuous type contact equipment is superior to single-stage equipment for both injection and cooling. At present, there is little more than an order of magnitude quantitative understanding of the phenomena occurring when steam, water droplets, and particulates are mixed--especially in equipment configurations that are likely to be useful in actual industrial gas cleaning applications.

In order to resolve the areas of uncertainty and to develop reliable data for engineering design, additional development effort is necessary. Effort should be focused on pilot scale work in order to develop data under realistic heat and mass transfer conditions. The importance of particle properties and concentrations also indicates that the effects of these parameters should be defined in more detail.

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APPENDIX D

CHARGED DROPLET SCRUBBERS AS PARTICULATE CONTROL DEVICES

INTRODUCTION

Control devices using charged drops as the collecting bodies are currently under study by several investigators.[1-4]* In these devices, the particulates contained in a dirty gas stream are charged and collected on the surface of droplets having an opposite charge. The size of the collection drops is chosen so that they can be readily removed by conventional control devices or will precipitate in their space-charged field. Theoretical aspects and limited experimental data on charged droplet scrubbers are reviewed next.

THEORETICAL ASPECTS

No complete theoretical analysis of charged droplet systems is available at this time. The earliest work on charged droplet systems appears to be that reported by Penney.[5] Kraemer and Johnstone discuss an electrified wet scrubber as part of their work on the collection of aerosol particles in the presence of electrostatic fields.[6] They present a general theoretical solution and experimental verification for the deposition of aerosol particles from a moving gas stream and suggest that an electrified wet scrubber would be one approach to the use of electrostatic forces for particle collection.

The use of charged drops to collect or agglomerate fine particulates has been reviewed in detail by Melcher and Sachar.[2]* They consider mechanisms using injected droplets which fall between those of inertial scrubbers and electrostatic precipitators. Their classification is shown in Figure D-1. Categories I and II are mechanical and electrical scrubbers. It is interesting to note that Melcher and Sachar find the electrical scrubber to be roughly competitive with the mechanical scrubber in water usage, particularly for fine particles. Energy requirements were not

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* Work in Refs. 2 and 4 is being supported by EPA, Control Systems Laboratory.

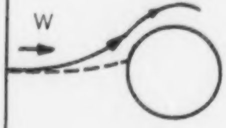
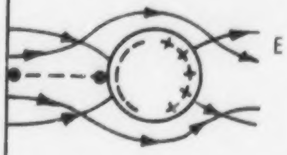
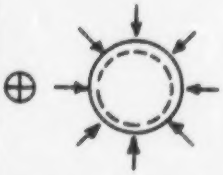
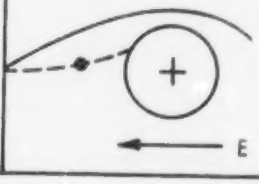
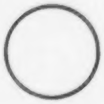
Particle Drop	Uncharged	Charged; No Ambient E	Charged, Ambient E
Uncharged	I. Mechanical scrubbers; inertial impact from drop injection. 		IV. Collection on half-surface of polarized drop having no net charge. 
Charged; no ambient E		III. Drops having net charge collect particles having net opposite charge. 	
Charged, and ambient E	II. Electrical scrubbing; inertial impact through electrical propulsion of drops. 		V. Combination of II, III and IV 

Figure D-1. Classification of particle-drop interaction mechanisms[2] (Melcher and Sachar) evaluated. Classes III and IV consist of two basic agglomeration mechanisms for charged particulates. Class V is a hybrid category which combines mechanisms II, III, and IV with a conventional electrostatic precipitator.

Melcher and Sachar also discuss simple models for charged drop-particle interactions corresponding to the various classifications shown in Figure D-1. The purpose of the development of models was to highlight the dependence of the various collection mechanisms on system parameters. Attention was focused on Class III interactions since they appear to hold the most promise for a new approach to particulate control.[2]

In subsequent work, Melcher, et al., identified three critical time constants which they feel characterize the limitations of using charged drops for collecting small charged particles.[7,10] First, there is the time $\tau_R = \epsilon_o/NQ\Phi_D$, where in MKS units $\epsilon_o = 8.85 \times 10^{-12}$, N is the droplet density, Q is the charge per drop and Φ_D is the mobility of the drop. If there is only one polarity of charged drops, this time constant represents a time for these drops to be electrostatically self precipitated on the walls of the channel or containers. If the system is composed of both positive and negative drops, then the same time constant (but based on one of the two families of particles) represent self agglomeration or at least electrical discharge among the droplets.[7]

A time constant playing a similar role for the fine charged particles (which are to be removed by collection on the drops) is defined as $\tau^* = \epsilon_o/nq\Phi_f$ where n, q, and Φ_f are respectively defined as the number density, charge per particle, and mobility of the fine particles. Again, in the case of unipolar charging, this is the typical time for self precipitation of like-charged fine particles and with bipolar charging it is typical of the time required for self agglomeration. Finally, there is a third characteristic time $\tau_d = \epsilon_o/NQ\Phi_f$ which typifies the time required for the fine particulate to be collected by or at least be discharged by the droplets.

Melcher states that one of the most fundamental limitations on what can be done using charged drops to collect fine charged particles comes from the fact that τ_R is typically much shorter than τ_d. This is true because the mobility is generally proportional to the size of the particle and hence $\emptyset_D >> \emptyset_f$. Thus, the charge from the drops will be available to cause the collection of the small particles only for a time which is short compared to the time actually required to collect a significant fraction of the small particles.[7]

Professor Pilat at the University of Washington has also performed some theoretical analyses of charged droplet scrubbers as a part of his work on these systems. The details of his analysis were not available to use in this report.[3]

Professors Donald Hanson and Charles Wilke at the University of California, Berkeley, have investigated space-charge precipitators augmented by water droplets. Basically, the space-charge precipitator developed at the University of California consists of two parts: (1) a short section where both the particles and the added drops are charged by high voltage coronas; and (2) a section of grounded tubes or plates on which the particles and drops are collected. In the collecting section, the drops and particles migrate to the surfaces, where they coalesce and flow from the precipitator as a slurry.

Both theoretical and experimental studies on space-charge precipitation have been conducted at the University of California. Theoretical studies have focused on an analysis of the nature of drop and particle charging and the analysis of drop production. An engineering design for a pilot-scale space-charge precipitator was also proposed.

EXPERIMENTAL STUDIES OF CHARGED DROPLET SYSTEMS

Only limited experimental work on charged droplet systems has been conducted to date. Professor Pilat at the University of Washington has a pilot plant version of an "Electrostatic Droplet Spray Scrubber" in operation.[3] In this device the droplets are charged positively and the particulates negatively. The efficiency of the scrubber was increased (when the charges were added) from 68.8% to 93.6% for 1.05-micron DOP droplets (standard deviation of 2.5) and from 35% to 87% for 0.3-micron droplets. The scrubber requires about 0.7 liters of water at 100 psi/m^3/min (5 gal at 100 psi/1,000 cfm) and a small amount of power.[3] It is interesting to note that the efficiencies reported by Pilat are much higher than would be predicted by the theoretical models proposed by Melcher. The pessimistic position expressed by Melcher regarding charged droplet scrubbers would appear to require further investigation.

TRW, Inc., is reported to have a proprietary charged droplet scrubber which they are now developing. This device is claimed to have an efficiency comparable to a venturi scrubber, but to require only about 0.02 hp/m^3/min (0.5 hp/1,000 cfm). A unit is currently in operation in Japan. Reliable efficiency data for fine particulates are not available.[4] The Control Systems Laboratory is currently funding additional work on charged droplet scrubbers at TRW, Inc.

Experiments on a laboratory-scale space charge precipitator were conducted at the University of California. The experimental unit, depicted in Figure D-2, handled 0.85 m^3/min of air on a dry basis at a velocity of 3 m/sec. The fog injection system and the corona charging system were built according to specifications developed in the engineering design calculations.[1,8,9] The particulate material injected included, during various experiments, tobacco smoke, oil mist, and several other dusts.[1]

Tables D-1 and D-2 show the extent of precipitation of iron oxide dust with and without the injection of fog. Table D-1 shows that about 92% of the iron oxide was precipitated by normal electrostatic precipitation when no fog was added. Table D-2 shows 100% precipitation of the iron oxide, within the limits of detectability, when fog was added. The colorimetric data shown in Table D-2 were reported to be accurate to within about 1% on the percent precipitation, and results in Table D-2 should, therefore, be interpreted as 99+% precipitation.[5,6] The simple experiments summarized in Tables D-1 and D-2 probably do not accurately model a practical system. However, they do suggest that charged droplets have some potential for particulate collection.

Energy requirements for charged droplet systems are relatively uncertain. Kostow's[1] calculations yield a total energy requirement of less than 0.02 hp/m^3/min (0.5 hp/1,000 cfm). Melcher and Sachar[2] do not calculate energy requirements. If we assume that a charging and collection system for their Types III or IV mechanisms has energy requirements similar to that for a conventional electrostatic precipitator, we can estimate the electrical power at less than 0.04 hp/m^3/min (1.0 hp/1,000 cfm). Melcher and Sachar's model suggests water mist loadings of less than 0.02 kg/m^3/min (1 lb/1,000 cfm), which should require less than 0.04 hp/m^3/min (1.0 hp/1,000 cfm) to produce. Thus, total energy requirements of about 0.08 hp/m^3/min (2 hp/1,000 cfm) appear likely for charged droplet systems.

CONCLUSIONS

The currently available data on electrostatic scrubbers and related devices using charged drops indicate some potential for the collection of fine particles. However, adequate data are not now available for a comprehensive analysis of any of the existing devices or of the basic mechanisms involved. While the ultimate efficiency and usefulness of these devices cannot be determined accurately at this time, it should be noted that the major workers in this field estimate, from their experience and analysis, that efficiencies comparable to, but not much better than, conventional electrostatic precipitators can be obtained for submicron particles.[3,7,10]

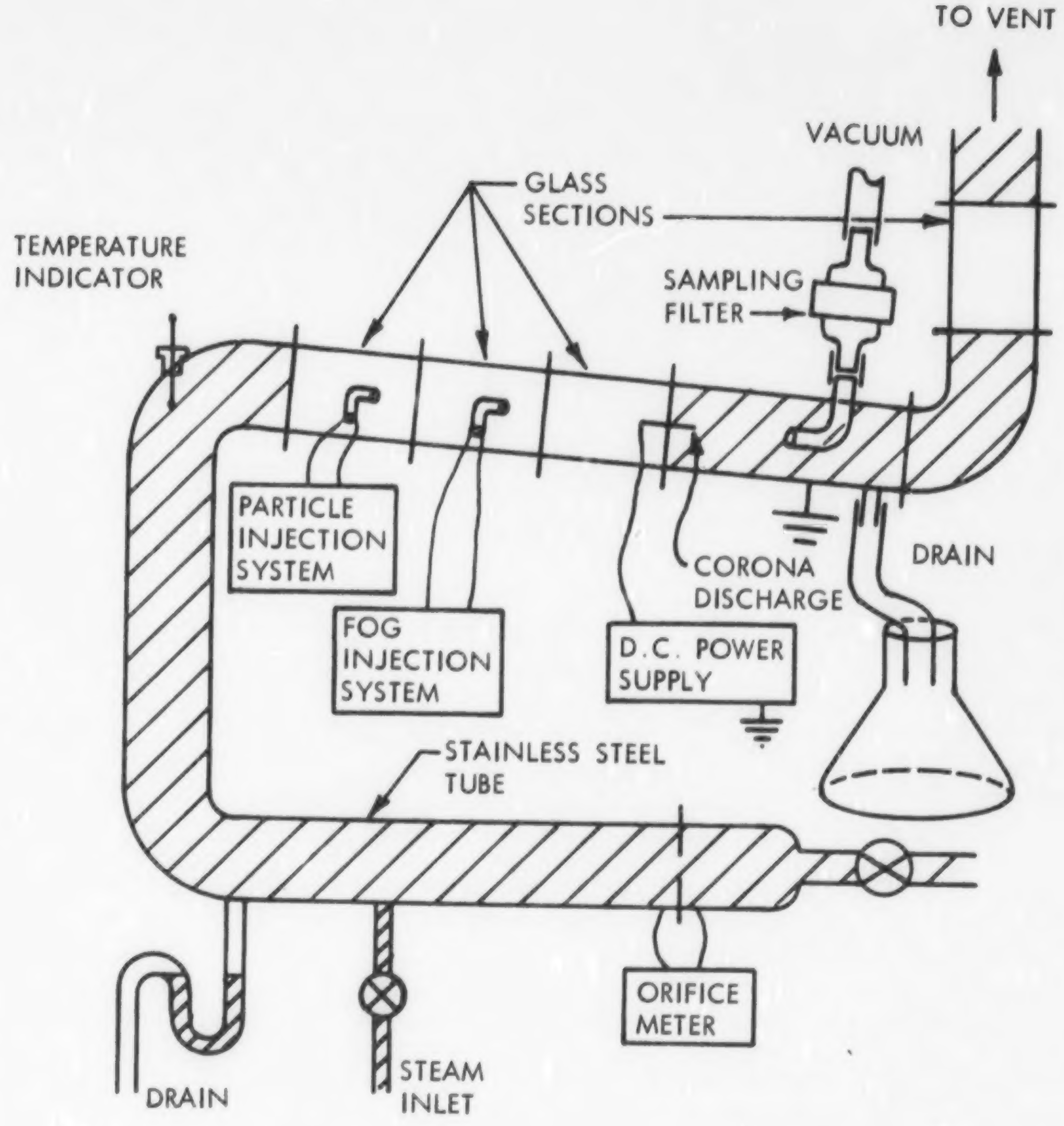


Figure D-2. Experimental apparatus for space-charge precipitation

Table D-1. IRON OXIDE DATA, NO FOG ADDED TO THE PRECIPITATOR

Run	Corona Off "A"	Corona On "A"	Precipitation (%)
1	0.900	0.024	97.3
2	0.670	0.104	84.5
3	0.546	0.019	96.5
4	0.695	0.056	91.9
5	0.715	0.068	90.5
6	0.945	0.196	79.8
7	0.620	0.008	98.7
8	0.229	0.010	95.6
9	0.222	0.012	94.5
10	0.168	0.004	97.6
11	0.215	0.004	98.1
12	1.00	0.202	79.8
13	0.180	0.004	97.8
14	0.219	0.024	89.0
15	0.314	0.034	89.2

Average Precipitation, % = 92.1%

A = Absorbance as measured on the colorimeter; Absorbance being directly proportional to the amount of iron present.

Table D-2. IRON OXIDE DATA, WITH FOG ADDED TO THE PRECIPITATOR

Run	Corona Off "A"	Corona On "A"	Precipitation (%)
1	0.180	0.0	100.0
2	0.292	0.0	100.0
3	0.094	0.0	100.0
4	0.513	0.0	100.0
5	0.133	0.0	100.0
6	0.064	0.001	99.5
7	0.111	0.0	100.0
8	0.105	0.0	100.0

Average Precipitation, % = 100.0

A = Absorbance as measured on the colorimeter; Absorbance being directly proportional to the amount of iron present.

Potential advantages of charged droplet systems in comparison to conventional electrostatic precipitators include the ability to clean gases at lower voltage levels and elimination of problems of dust reentrainment and of dust resistivity frequently encountered in conventional electrostatic precipitators. Advantages with regard to wet scrubbers include lower water usage and lower pressure drop at the same collection efficiency.

Disadvantages in comparison with conventional electrostatic precipitators include:

1. Need to produce and charge drops;

2. Premature space charge precipitation of drops on walls of device;

3. Neutralization of charge of drop upon collection of oppositely charged particulates; and

4. Need to handle wastewater stream.

Additional research and development activity on charged droplet systems is recommended. Emphasis should be placed on experimental work on bench-scale or pilot-scale model systems so that meaningful engineering design data are obtained.

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APPENDIX E

FOAM SCRUBBERS AS PARTICULATE CONTROL DEVICES

INTRODUCTION

The addition of surface-active agents to water produces a foam and the effectiveness of the collection of particulates by bubbles in wet scrubbers can sometimes be increased by generating a foam. Wet scrubbers of this type, called foam scrubbers, have been reported as being effective for the collection of fine particles.

A foam scrubber consists of at least two components: the foam generator and the particle collector. If the foam does not collapse after the particle collection step, a third component is required--a foam destroyer. The potential of foam scrubbing to control particulates, especially fine particles, is discussed in the following sections. Available theoretical and experimental information is presented and assessed.

THEORETICAL ASPECTS OF FOAM SCRUBBING

Particulate collection in a foam scrubber is effected by the use of bubbles. At present, a comprehensive theory for foam scrubbers is not available. Some insight into the potential of the method can be obtained from the analysis of particle collection by bubbles reported by Fuchs[1/] and Calvert.[2/] The analysis of Fuchs which pertains to the absorption of aerosols by bubbles is general and does not relate to any specific equipment configuration. Calvert's analysis relates to sieve plate columns. The more general analysis of Fuchs will be used to indicate the potential performance of a foam scrubber.

Fuchs[1/] has derived expressions for the ratio of the number of particles deposited per centimeter of path to the total number in the bubble for deposition by impaction, sedimentation, and diffusion. This ratio is termed the coefficient of absorption (α) and has the units of reciprocal centimeters.

For inertial deposition,

$$\alpha_I = \frac{9 \; v_b \; \tau}{2 \; R_b{}^2} \tag{E-1}$$

where v_b = Ascending velocity of bubble (cm/sec)

R_b = Radius of bubble (cm)

and,

τ = Force of internal friction per square centimeter

$= \frac{D_p^2 \rho_p}{18 \; \mu_g}$

D_p = Diameter of particle (cm)

ρ_p = Density of particle

μ_g = Viscosity of gas in poise.

Substitution for τ in Eq. (E-1) results in

$$\alpha_I = \frac{9}{2} \frac{v_b \; D_p^2 \; \rho_p}{R_b^2 \; 18 \; \mu_g} = \frac{1}{4} \frac{v_b \; D_p^2 \; \rho_p}{R_b^2 \; \mu_g} \quad . \tag{E-2}$$

For absorption due to sedimentation,

$$\alpha_g = \frac{3 \; g \; \tau}{4 \; R_b v_b} \tag{E-3}$$

where R_b, v_b and τ represent parameters described under Eq. (E-1) and g = acceleration due to gravity (cm/sec^2).

By substituting the expression for τ in terms of particle size, Eq. (E-3) reduces to

$$\alpha_s = \frac{3\ g\ D_p^2\ \rho_p}{4\ R_b v_b\ 18\ \mu_g} = \frac{1}{24}\ \frac{g\ D_p^2\ \rho_p}{R_b v_b\ \mu_g} \qquad \text{(E-4)}$$

For diffusive absorption,

$$\alpha_D = 1.8 \left(\frac{D}{v_b\ R_b^3} \right)^{1/2} \qquad \text{(E-5)}$$

where D = diffusivity of particles (cm^2/sec), and other parameters have the same representation as those mentioned above.

The collection absorption due to all three mechanisms (α_t) can be expressed as

$$\alpha_t = \alpha_I + \alpha_S + \alpha_D\ . \qquad \text{(E-6)}$$

It is apparent from the original derivation by Fuchs[1] that the coefficient of absorption α, is, in reality, the efficiency of collection, inasmuch as it is a ratio of the actual number of particles deposited per bubble to the theoretical number of particles that can be deposited per bubble. It is apparent that the efficiency is primarily a function of particle size (D_p), bubble velocity (v_b), and bubble radius (R_b).

The preceding analysis is undoubtedly greatly simplified compared to the actual processes in a foam scrubber, but it serves to point out some of processes that are operating in such a device. Fuchs states that the fact that absorption of dust in bubbling can sometimes be increased by adding surface-active materials to the water is partly explained by a reduction in bubble size, partly by the increased collision efficiency of dust particles with the walls of the bubbles, and partly by the comparatively large residence times of the aerosol in the foam cells. Fuchs also discusses the results of several studies on the influence of surface-active agents on the collision efficiency of particles with bubbles and droplets and concludes that the effect of wetability of particles becomes significant only when the kinetic energy of collision is small.

EXPERIMENTAL STUDIES OF FOAM SCRUBBING

Limited experimental study of foam scrubbers has been reported in the technical literature. References 4-6 report good results for the absorption of aerosols by foams. Reference 7 describes a Japanese patent for a foam scrubber. Experimental data on the system were not reported.

Professor R. Mahalingham at Washington State University has recently initiated a study of wet scrubbing using a high-expansion foam.[9] No experimental data are available from his work to date.

Javorsky[8] describes a foam bed scrubber for separating fine dust from gases. Figure E-1 presents a cut-away diagram of the system--the Centrifoam Scrubber. The Centrifoam Scrubber is a product of Alfa-Laval AB, Separation Division, Tumba, Sweden. The Centrifoam Scrubber as described by Javorsky consists of a vertically arranged cylindro-conical vessel with an inlet and distribution facilities for the contaminated gas at the bottom, which is also fitted with a paraxial sludge outlet. The greater part of the vertical vessel is filled with a foam bed, which is supplied continuously or at predetermined intervals from a foam inlet in the cylindrical part of the vessel and is supported by the grid of the gas distributor.

The foam, the chemical composition of which may vary considerably but is generally quite simple, is dense yet mobile. It may be obtained by dispersing air in a suitable liquid to such an extent that the liquid content of the resultant foam will be 0.2-3% by volume. The interfacial areas enveloping the innumerable bubbles of the foam bed provide efficient barriers to the gas-borne dust particles, which are intercepted.

In the Centrifoam Gas Scrubber, the particles are exposed to adhesion forces that make them adhere to the moist bubble interfaces at even the slightest contact. Hence, in the Centrifoam Scrubber the size of the dust particles is of minor importance, the smallest particles being separated almost as efficiently as the bigger ones.

Javorsky reports that the Centrifoam Scrubber has been tested with a variety of dusts and that collection efficiencies in the 90-97% range are obtained. Pressure drops are reported to vary from 6 to 28-mm water.

An installation on a foundry cupola in Sweden is also reported by Javorsky to clean over 3,000 m^3/hr of gas. The amount of water required to make the necessary foam does not exceed 20 liters/hr, the velocity of the gas is 1.6 m/sec, the foam number (i.e., the gas/liquid ratio when making the

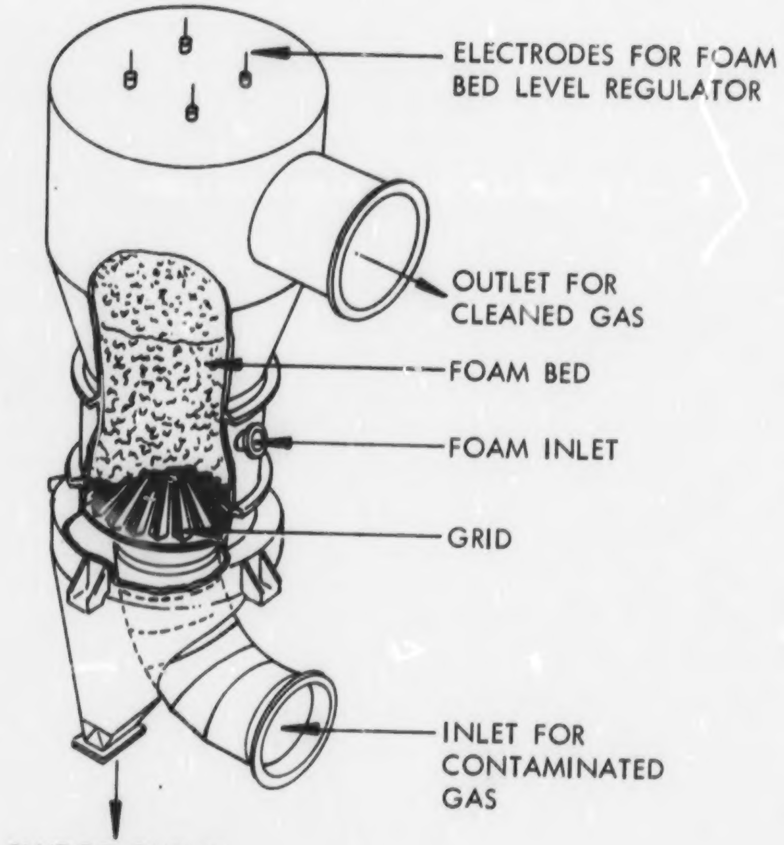
ELECTRODES FOR FOAM BED LEVEL REGULATOR
OUTLET FOR CLEANED GAS
FOAM BED
FOAM INLET
GRID
INLET FOR CONTAMINATED GAS
SLUDGE OUTLET

Figure E-1. The Centrifoam Scrubber[8]

the foam) is in the vicinity of 60, and the counterpressure is about 30-mm water at a bed thickness of 900 mm. Operating costs were reported to be about $0.10 per hour.

CONCLUSIONS

The limited information available suggests that the potential of foam scrubbing to control fine particles is good if the residence time is sufficient to collect fine particles. More detailed information is required regarding the mechanism of bubble formation, splitting, and destruction. Potential problems are formation of fine bubbles for good collection, foam destruction, and secondary foaming. Technical feasibility and optimum performance will rely on understanding the mechanisms associated with these processes as they will affect total energy and residence time requirements.

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APPENDIX F

ELECTRIFIED FILTERS AS PARTICULATE CONTROL DEVICES

INTRODUCTION

One potential technique for obtaining improved particulate control devices is to use electric fields in conjunction with the conventional fabric filter. Particles are normally brought to the surface of a fiber by diffusion and convection as well as by the effect of the flow field of the gas and retained on the individual fibers comprising the filter by surface forces. The static charges on most naturally occurring aerosols may also play a role in the collection and retention of the particles.

The magnitude of electrical forces compared to other forces that can be applied to particulates suggests that improvement in aerosol filtration should occur when electric fields are present in conjunction with fabric filters. Theoretical and experimental studies of electrified filters are discussed in the following sections.

INVESTIGATIONS OF ELECTRIFIED FILTERS

External fields, internal fields, and electrets have been used in conjunction with fiber filter systems. Each of these techniques is reviewed separately.

External Electrostatic Fields

If a filter is placed in an initially homogeneous electric field, the fibers will be polarized to produce an inhomogeneous electric field near the fiber surface. Neutral particles entering the filter will be polarized by the external field and will therefore interact with the field around the fiber. Any net charge on the particles will also interact with the local field.

The problem of the deposition of aerosol particles from an air stream of velocity v_g , in a homogeneous electrical field, E , has been studied theoretically by Zebel,1/ Kazutaka and Koichi,2/ and Rao et al.,3/ among others. Zebel developed a general theory for deposition upon an isolated, uncharged cylinder when the particles are charged or uncharged. Rao et al.[3] extended the theory by including the effect of the closeness of fibers on the deposition of charged particles by use of a three-cylinder model. The single-cylinder model of Zebel significantly overestimates the deposition of particles in low porosity filters because of the neglect of the interaction of neighboring fibers. The three-cylinder model proposed by Rao et al. predicts that the deposition on a given fiber will decrease as the porosity of the filter decreases--a result more in agreement with experimental observations.

Several experimental studies of filters in external fields have been carried out. All report substantial enhancement of the filter efficiency. Only Kirsch[4] has used a filter of known geometry. Kirsch found that $\eta = c\beta^{\gamma}$ where c and γ are constants ($\gamma = 2/3$, $c = 1$) for both idealized and real filters and η is the collection efficiency.

Internal Fields with Potential Applied to the Filter Elements

Walkenhorst[5] has studied filters consisting of arrays of insulated wire 0.08 mm in diameter (0.5 mm apart). Potentials of 600-1,000 V were applied to the wires, with the polarity reversed at frequent intervals to reduce the effect of the polarization of the collected dusts. Typical results are shown in Figures F-1 and F-2 for coal and quartz dusts at different relative humidities and gas stream velocities. The pressure drop at 10 cm/sec was less than 0.001 in. of water, although measurements were only extended to about 0.1 μm particles, these results suggest that efficient collection can be obtained for even smaller particles. Electric power consumption would be expected to be very low.

Electrets

Electrets are devices which have a "frozen-in" effective charge. As a consequence, electrets are the electrostatic analog of permanent magnets since an electrical field is produced without the application of external potentials. This field can be stable for long periods of time. If a filter is constructed from filters of an electret, inhomogeneous electric fields will occur around each fiber. It is then possible to obtain electrical enhancement of aerosol filtration without applying external fields or potentials.

Electrets have been investigated experimentally and theoretically by Ziekman.[6] Filters were successfully formed from electret fibers which

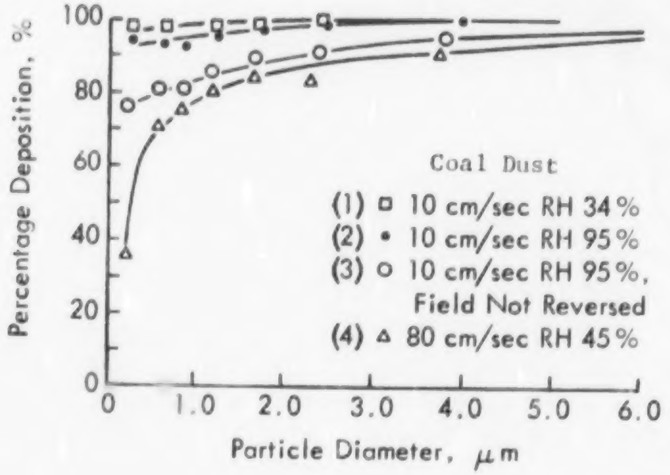

Figure F-1. Collection efficiency of wire grid filters with coal dust

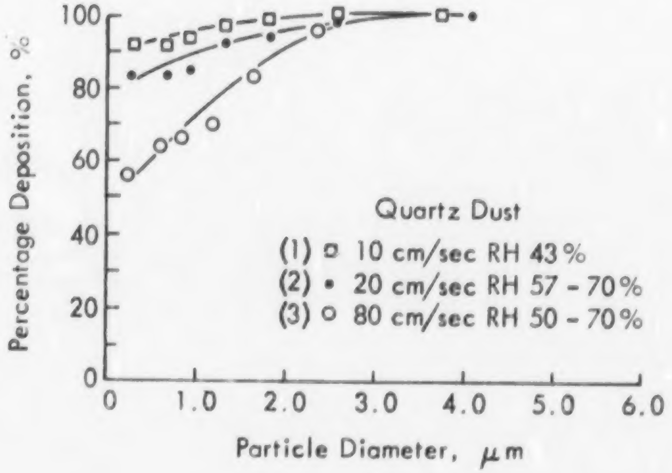

Figure F-2. Collection efficiency of wire grid filters with quartz dust were initially approximately 23 μm in diameter. These filters showed a penetration of 0.72 micron di-octylphtalate aerosols of less than 1% (compared to 80-90% for comparable "unelectrified" filters) at a pressure drop of less than 0.04 in. of water and a flow velocity of ~ 1.25 ft/sec. However, the penetration of the filter increases with particulate loading as shown in Figure F-3. This is the result of the cancellation of the electric field of the electret by the collected polarized aerosol particles. The data shown in Figure F-3 were taken with a filter 3 cm in diameter. Consequently, for a maximum penetration of 1% at a particulate loading of 2.3 g/m^3 (1 $grain/ft^3$), only about 0.006 m^3 (0.2 ft^3) of gas per square foot of filter could be treated before regeneration or replacement of the filter. Since it is not clear how readily an electret filter can be regenerated, this could be a major problem in an industrial application.

CONCLUSIONS

Available theoretical and experimental information indicates that electric fields can improve the collection efficiency of fabric filters. However, the lack of adequate data on filter systems suitable for industrial applications precludes a firm judgment on the potential usefulness of an electrified filter for industrial applications. Some intuitive statements of advantages and disadvantages can be proposed.

It may be possible to utilize a system composed of a conventional bag filter with an electrification addition. The field would be applied intermittently, e.g., just after cleaning, to maintain uniformly low penetration during the period of cake repair. The same combination operated continuously might have a positive benefit in reducing penetration of fine particles. The system might also combat re-entrainment of collected particles, however, deposited, due to electrostatic adhesion.

Another possibility involves usage of a more porous filter media in an electrified filter system to increase capacity, operate at lower pressure drop, or allow control of difficult sources. The economics and reliability of such a device is speculative.

Nearly all of the test work to date involved short-term effects. The test regimes were constructed to minimize or eliminate the other important filtration mechanisms. Further testing would be needed to document any improvement in collection efficiency when these other mechanisms are in operation, particularly with respect to fine particulates.

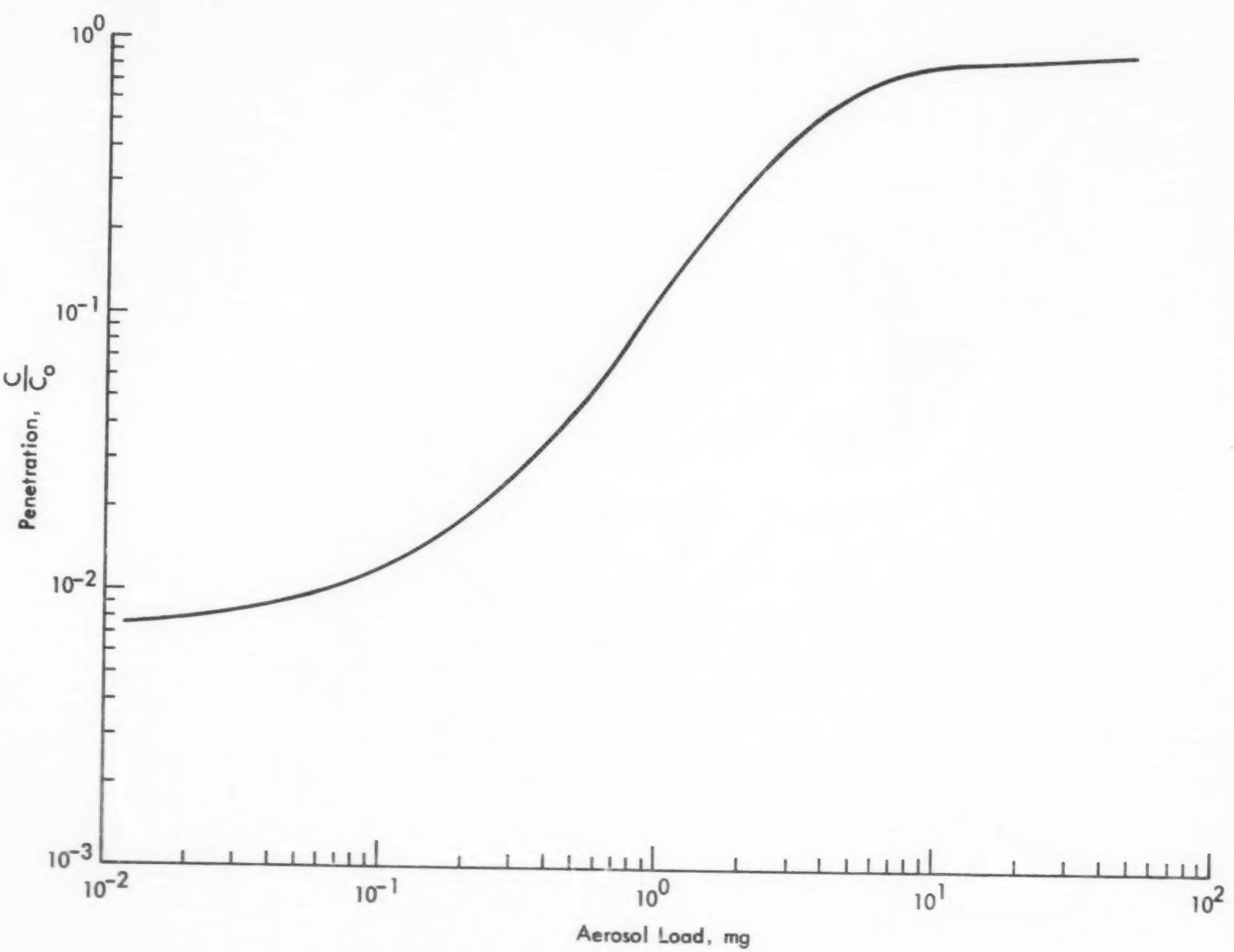

Figure F-3. Penetration load curve for electret filter

Nearly all tests utilized extremely low concentrations of aerosol. Consequently, for a short test run the deposition on the filter was light. Little information is available on the incremental effect due to electrostatic benefication when a more normal filter cake is present.

No studies investigated cleaning mechanisms, possible difficulties in cleaning, or penetration increase during cleaning. Cleaning of an electrified filter or an electrostatically assisted system will probably be more difficult than merely reversing polarity or turning off the field. There are some reservations as well when one considers introduction of an electrified filter into industries which collect dust having an explosive or fire hazard.

In principle, enhanced performance of fabric filters appears possible by the utilization of electric fields. It is not clear whether the improved performance of these filters will justify their use or whether electrical filters will be adaptable to the control of emissions from industrial processes. Further analysis is recommended with emphasis placed on experimental investigations of fabric filter configurations actually utilized in industrial applications. Theoretical studies are not recommended because of the inherent limitations of theoretical models of fabric filtration.

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APPENDIX G

GRANULAR BED FILTERS AS PARTICULATE CONTROL DEVICES

INTRODUCTION

The ability of porous beds of granular materials such as sand, coke, sintered materials, Raschig rings or similar materials to remove particles from gas streams has been appreciated for many years. Although granular beds have found practical application in atomic energy facilities and the filtering of small volume gas streams, application to industrial sources of particulate pollution has been limited--especially in the United States. In spite of the lack of extensive study and utilization of granular bed filters, enough evidence is available to suggest potential areas or sources where granular bed filters might be used to advantage to control fine particulates.

The following sections present a discussion of: (1) theoretical studies of granular bed filters; (2) experimental studies of granular bed filters; (3) areas of potential application; and (4) estimates of cost of granular bed filters.

THEORETICAL STUDIES OF GRANULAR BED FILTERS

Filtration of aerosols in a granular bed filter may result from the interaction of the following mechanisms: Brownian diffusion, inertial impingement, direct interception, gravity settling, thermophoresis, electrostatic attraction, and particle agglomeration. The nature and size of the dust or mist particles, the structure and size of the bed granules, and bed operating conditions will determine which of the collection mechanisms are dominant. Theoretical analysis of the performance of granular beds is difficult because of the many possible interactions of the mechanisms that may contribute to aerosol collection in granular beds.

Attempts have been made to adapt the results of studies of aerosol filtration by fibrous filters to granular bed filters.1-3/ Since the mechanism of collection on granules is essentially the same as in fiber beds or mats, it seems plausible that correlations developed for fiber beds could be used to describe granular bed behavior. Attempts to use existing correlations for fiber beds and mats to predict the performance of granular filters have met with limited success. Extrapolations of collection efficiency equations developed for fiber filter systems to granular filters result in predictions of poor performance for granular filters. These predictions are generally at variance with experimental observations.

The major problems appear to be:

1. Size differences between the fibers used in typical filters (10 μm) and the granules that are of greatest potential interest (6-60 mesh) from the standpoint of pressure drop; and

2. Lack of knowledge regarding the controlling size dimension for a granular filter.

In granular filters, the key dimension may be the size of a small protuberance or angular sections on the surface of the granules and not an average granule diameter. Particle agglomeration occurring in the tortuous paths between the collecting granules is probably also important to the collection process.

At present, there are no useful models for aerosol filtration in granular beds. Our knowledge of the performance of granular beds has been obtained essentially from experimental studies at both the laboratory and pilot-scale level. Pertinent results of experimental studies are presented in the next section.

EXPERIMENTAL STUDIES OF GRANULAR BED FILTERS

Experimental investigations of aerosol filtration by granular beds have been performed on fixed and moving beds and beds augmented by electrostatic and sonic forces. Although the studies have not been extensive in either category of granular beds, experimental work has identified many of the salient features of granular bed filtration.

Fixed and Moving Beds

A major portion of the initial experimental work on granular beds has been done by investigators associated with the atomic energy field. Limited work has been done on the filtration of aerosols emitted by various industrial operations. Reference 11 presents a review of published information on the use of sand-bed filters in industrial and atomic energy facilities.

Table G-1 presents a summary of selected experimental studies of granular bed filtration. The studies summarized in Table G-1, while not encompassing all the investigations conducted, are representative of the type of studies performed to date. The results of the experimental studies on a laboratory scale indicate that granular bed filters perform in many respects in a manner analogous to fiber filtration systems. Specific performance characteristics of granular filters identified by laboratory studies include:

a. At constant face velocity, there exists a particular aerosol size that exhibits a maximum penetration of a granular bed.

b. Percentage of penetration by an aerosol in a granular bed is a function of aerosol particle size, aerosol type, face velocity, bed depth, degree of bed packing, granule particle size, and granule shape.

c. Particle size of the aerosol corresponding to maximum penetration decreases with increasing face velocity.

d. Aerosol penetration decreases with increasing bed depth up to a limiting bed depth.

e. Maximum penetration by an aerosol occurs at lower face velocities with increasing bed depth.

f. Aerosol penetration decreases as the granule size is decreased.

g. Aerosol penetration of granular beds composed of rough, irregular granules is less than that of beds composed of smooth granules of the same characteristic diameter.

h. Physical characteristics of the aerosol influence bed performance--aerosols which tend to agglomerate are more readily collected.

Meager results have been reported on pilot-scale studies of granular filters operating on industrial sources of particulate pollution. Limited data available indicate collection efficiencies in the range 85-98%. Collection efficiencies were found to increase with increasing grain loading--indicating that agglomeration may contribute to particle collection in industrial applications. Pressure drops in the pilot-scale tests were reported to be in the range 0.5-5.0 in. H_2O.

Table C-1. SUMMARY OF SELECTED EXPERIMENTAL INVESTIGATIONS OF GRANULAR BED FILTERS

Investigator	Granular Bed Configuration	Test Conditions	Parameters Studied	Bed Performance	Comments
I. Laboratory Studies					
a. Thomas and Yoder[4]	**(a) Bed Type: Fixed Bed** **(b) Bed Material: Sand** **(c) Average Sand Grain Diameters: 0.161 cm, 0.071 cm, 0.036 cm** **(d) Bed Height: 3.6 and 7.6 cm**	Aerosol: DOP Aerosol Particle Size: 0.1 - 1.0 µm Face Velocity: 0.11 to 2.2 cm/sec	Sand Particle Size, Sand Particle Shape, Face Velocity	(a) Penetration varied with sand particle size -- decreasing diameter of sand (b) Rough and irregular sand showed higher collection efficiency then smooth sand (c) Collection efficiencies varied with sand particle size, face velocity, and aerosol particle size. Efficiencies ranged from 40 to 99.8%	Experimental result demonstrated the existence of an aerosol size of maximum penetration of about 0.3 µm. Particle size of maximum penetration decreased with increasing face velocity.
b. McFee and Sedlet[5]	**(a) Bed Type: Fixed Bed** **(b) Bed Material: Sand** **(c) Sand Grain Diameter: 0.036 to 0.071 cm** (d) Bed Height: 15.2 to 76.2 cm	Aerosol: Pu-U-Mo Alloy Fume Aerosol Particle Size: Geometric Mean = 0.07 µm, Standard Deviation = 2.7, (Discrete sizes ranged from < 0.02 to 4 µm) Face Velocity: 0.3 to 40.5 m/min Aerosol Grain Loading: Approximately 0.11 g/m^3	Bed Height, Face Velocity	(a) Penetration through 15.2 cm of sand varied from 0.08 to 0.57% over range of face velocities from 0.3 to 40.5 m/min. Maximum penetration of 0.57% occurred in range of 12.2 to 24.4 m/min (b) Penetration through 76.2 cm of sand varied from 0.004% at 8.5 m/min to 0.019% at 1.5 m/min (c) Penetration decreased with increase in bed depth up to depth of 30.5 to 45.7 cm, but relatively small improvement occurred for beds of greater depth	Experimental results indicate the percentage of penetration varies with aerosol particle size, face velocity, bed depth and degree of packing of bed. Experimental observations confirm and extend findings of Thomas and Yoder.

Table G-1. (Continued)

Investigator	Granular Bed Configuration	Test Conditions	Parameters Studied	Bed Performance	Comments
				d) Maximum penetration occurs at lower face velocity with increasing bed depth e) Pressure drop through sand varied with bed depth and face velocity and ranged from 0.04 to 7.5 in. Hg	
c. Kovach and Hannan[6]	(a) Bed Type: Fixed Bed (b) Bed Material: Carbon (c) Granule Size: 0.4 to 0.16 cm (d) Bed Height: 38 cm	Aerosol: DOP, Fly Ash Aerosol Particle Size: Fly Ash -- 5 to 100 μm Face Velocity: 3 to 61 m/min	Aerosol Type, Face Velocity, Granule Size	a) Penetration varied with bed granule size -- decreasing with decreasing granule size b) Penetration varied with face velocity	Penetration of fly ash aerosol was less than that for DOP aerosol. However, particle size of fly ash varied over a wide range, and effect may be due to both changes in particle size and aerosol type.
d. Paretsky[2]	(a) Bed Type: Fixed Bed (b) Bed Material: Sand (c) Sand Particle Size: 10 to 14 and 20 to 30 mesh (approximately 0.15 cm and 0.07 cm) (d) Bed Height: 3.7 to 19.2 cm	Aerosol: Polystyrene Aerosol Particle Size: 1.1 μm Face Velocity: 0.3 to 80 cm/sec	Face Velocity, Bed Height, Granule Size	a) Penetration at a given face velocity decreased as the granule size decreased	Results in agreement with those reported by other investigators.
e. Zahradnik, et. al.[7]	(a) Bed Type: Shaft Filter (bed of slowly falling granules through which gas stream passes horizontally) (b) Bed Material: Alkalized alumina (1/16 in. beads) (c) Bed Width: 30.5 cm	Aerosol: Fly Ash Aerosol Particle Size: 11% < 13.7 μm Gas Mass Velocity: Up to 730 kg/hr/m^2 Fly Ash Loading: 4.6 to 6.9 g/m^3	Gas Mass Velocity	a) Collection efficiency: 99% at flow rate of 0.88 m^3/min and gas temperature of 400°F b) Pressure drop: 5.1 cm H_2O	Primary intent of study was to investigate simultaneous removal of fly ash and SO_2 by shaft-filter system.
f. Squires[8]	(a) Bed Type: Fixed bed with intermittent movement of solids (b) Bed Material: Sand (c) Bed Width: 3.5 cm (d) Sand Particle Size: Approximately 0.05 cm	Aerosol: Fly Ash Face Velocity: 3.65 m/min Fly Ash Loading: 4.6 to 9.2 g/m^3	Puffback Cleaning	a) Collection Efficiency: > 99% b) Pressure drop: 1.3 cm H_2O	High collection efficiency may be due in part to preagglomeration of fly ash before entering filter

Table G-1 (Concluded)

Investigator	Granular Bed Configuration	Test Conditions	Parameters Studied	Bed Performance	Comments
g. Ducon Company[3/]	Bed Type: Fixed bed with reverse gas flow cleaning	Aerosol: a) Iron oxide from oxygen-lanced electric arc furnace b) Iron oxide from oxygen-lanced open hearth furnace c) Nickel ore d) Fly ash e) Talc dust f) Plastic dust Face Velocity: 0.26 m/sec	Aerosol Type, Inlet Grain Loading (4.6 to 11.4 g/m^3)	a) Collection efficiency ranged from 98 to 99.9% b) Pressure drop: 10.1 to 15.2 cm H_2O	Collection efficiency was found to be higher for the finer sized iron oxide aerosols than for coarse fly ash. Indicates that physical characteristics of aerosol are an important factor in performance of filter -- possibly with regard to agglomeration behavior.
II. **Pilot Scale Studies**					
a. Ducon Company[9/]	Bed Type: Fixed bed with reverse gas flow cleaning Bed Material: Sand Sand Particle Size: 760 μm	Aerosol: Catalyst dust from fluid catalytic cracker (primary cyclone) Gas Flow Rate: 13.5 to 28.3 m^3/min Gas Temperature: 700 to 900°F Inlet Grain Loading: 0.34 to 1.95 g/m^3		a) Collection efficiency ranged from 85 to 98% b) Bed performance influenced by face velocity, back-cleaning cycle, bed particle size	Collection efficiency of bed varied with changes in inlet grain loading -- increasing with increasing grain loading
b. Strauss and Thring[10/]	Bed Type: Crushed brick Granule Size: 0.25 to 0.76 cm Bed Thickness: 2.5 to 26.7 cm	Aerosol: Fume from open hearth furnace Face Velocity: 0.3 to 1.02 m/sec Inlet Gas Temperature: 450° to 970°C Inlet Aerosol Loading: 0.46 to 22.9 g/m^3	Face Velocity, Bed Thickness, Inlet Gas Temperature, Inlet Grain Loading	a) Collection efficiency ranged from 85 to 98% b) Pressure drop: 1.01 to 11.9 cm H_2O	Variables not well controlled. However, on the average, higher collection efficiencies were noted at higher inlet dust loadings

Augmented Beds

The collection efficiency of granular beds can be increased by the use of augmenting forces. Limited work has been done with electrostatically augmented granular beds. Experimental and theoretical work is discussed in the following paragraphs.

The filtration efficiency of granular beds can be enhanced by electrostatic augmentation. If the filtration region is immersed in an electrostatic field, the dust particles will be driven in a direction that tends to increase the probability of impact between the particles and the filter medium.12/

If the dust particles are initially uncharged, the electric field will induce an electrical dipole in each particle which tends to align each particle with the electric field. This tends to orient the particle in such a way that the negative end of the dipole contacts the positive surface charge of the filter medium, and similarly, the positive ends tend to contact the negative surface charge of the medium. The result of this is that the collection efficiency is increased somewhat by the attractive force between the dust particles and the filter medium.

The filtration efficiency of packed bed filters can be further enhanced if the dust particles are electrically charged prior to introduction into the bed. If charged particles are introduced into the filter medium with a superimposed electric field, the dust particles are driven in the direction of the electric field. Thus, the probability of collection and the retentive forces for the dust particles are both increased by the addition of the electrostatic augmentation.

Particle collection theory for turbulent flow electrostatic precipitation shows that particles are captured only in the boundary layer of the gas stream adjacent to the collection electrodes. In conventional electrostatic precipitators, the interelectrode space is largely inactive for particle collection. This problem is significantly reduced in the augmented bed collector since the entire surface of the filter medium acts as the collection surface. This results in a significant increase in the collection area for a given volume of collector in comparison to that for a conventional precipitator. It seems probable from the above considerations that high collection efficiency, even for small particles, can be attained with electrostatic augmentation.12/

A study of the collection of submicron aerosol particles on electrified granular beds was carried out by Research-Cottrell, Inc., Bound Brook, New Jersey.[13] Collection of particles occurred in a bed of 3-6 mm glass beads held between two screens maintained at different electrical potentials (Figure G-1). Upstream of the glass spheres was a zone where the aerosol particles were given an electrical charge. Data taken on collection of a 0.6-0.7 μm methylene blue aerosol are shown in Figure G-2.[3] An efficiency of 99.5% was obtained in a bed under 5.1 cm thickness with a pressure drop of 0.51 cm wg and at the relatively high face velocity of 0.6 m/sec (2 ft/sec).

POTENTIAL AREAS OF APPLICATION OF GRANULAR BEDS

The most viable applications of granular beds as devices to control fine particle emissions are on sources which require the control of effluents under both corrosive and high temperature conditions. Metallurgical operations of various types are potential sources where granular beds may function as control devices. A particularly attractive application would be where the granular bed material can serve as charge material to a subsequent processing step.

Granular beds have been used in Europe in recent years on selected sources. While the use of granular beds in Europe has not been directed to the control of fine particulates, granular beds have been used successfully on cement and lime kilns, asphalt dryers, and clinker-coolers.[14] Rex Chainbelt, Inc., has introduced a dual-bed granular bed system into the U.S. by becoming the U.S. licensee for Gesellschaft für Entstaubungsanlagen's gravel-bed filter system, which has reported collection efficiencies of 99.5% or better. The Rex Chainbelt gravel-bed filters remove heavier dust particles by expanding and slowing the velocity of the air volume--the semi-cleaned gas is then passed over a bed of uniform-size round-quartz gravel, which breaks up the gas flow into many streams and allows the fine particles to be trapped. Detailed testing of this system has not been conducted to date, and its performance capability is not established.

ESTIMATES OF COSTS OF GRANULAR BEDS

Meager quantitative data are available on the costs of granular filters. Lapple, in a review of dust collectors, stated that fine-packed beds (< 4 mesh) are suitable for particle diameters of < 1 μm and have a 2-25 cm water pressure drop, a power comsumption of 0.007-0.07 kw/m^3/min (0.2-2.0 kw/1,000 cfm) and an initial cost of \$71-\$177/m^3/min (\$2-5/cfm); coarse beds (> 4 mesh) can filter particles as small as 5 μm diameter with a pressure drop of 0.51-5.1 cm water and a power consumption of 0.0035-0.018 kw/m^3/min (0.1-0.5 kw/1,000 cfm).

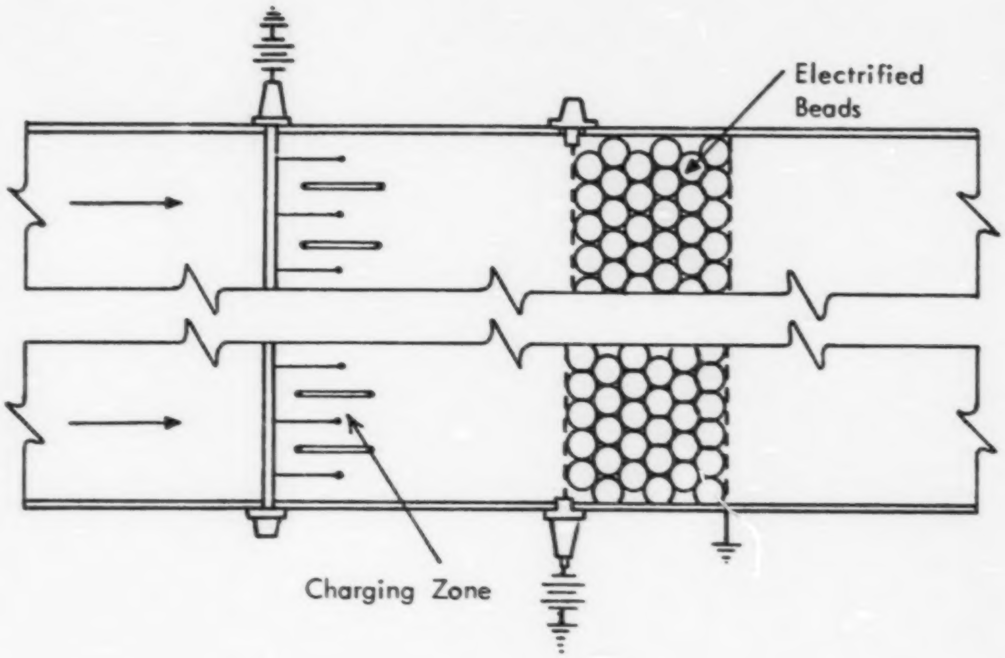

Figure G-1. Electrified packed bed

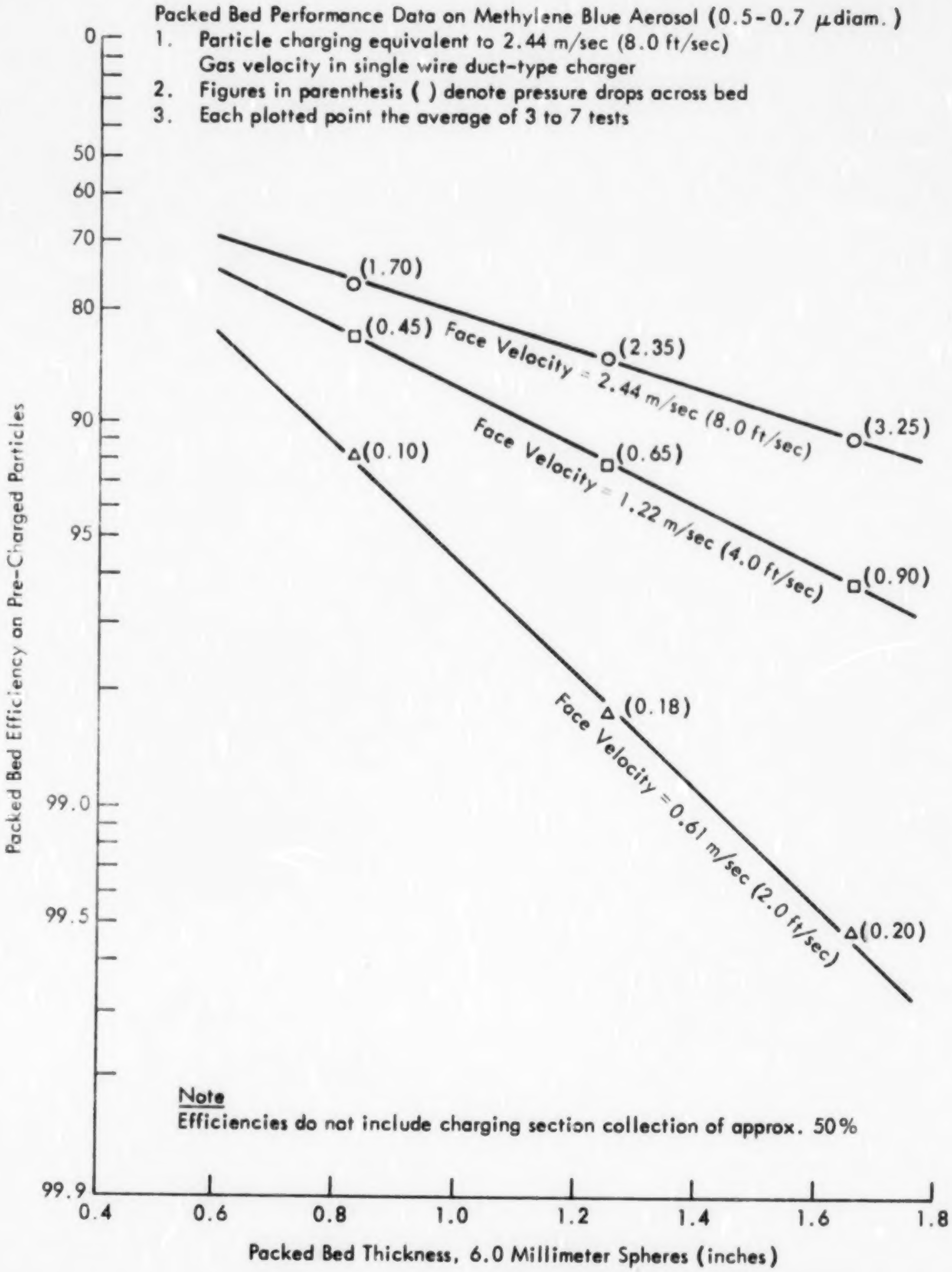

Figure G-2. Performance characteristics of electrostatically augmented packed bed

Cost estimates of various granular bed filter configurations are reported in Ref. 3. Installed costs for new power plants, based on the assumption of installation by the power company, for the granular beds functioning only as dust collectors were estimated at \$78-\$102 m^3/min (\$2.20-\$2.90/cfm). By comparison, electrostatic precipitators were estimated to cost between \$67-\$78/m^3/min (\$1.90-\$2.20/cfm) for the same installation.

CONCLUSIONS

With the possible exception of electrically augmented systems, granular beds do not offer any significant improvements in fine particulate control. Additional research on unaugmented systems is not recommended. Electrically augmented systems should be evaluated in conjunction with other electrified filter systems.

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APPENDIX H

FLUID BEDS AS PARTICULATE CONTROL DEVICES

INTRODUCTION

Investigations of fluid beds as particulate filtration media are quite limited. Only a few studies have been made over the years even though fluidized beds offer advantages of low pressure losses and ease of replacement of the bed for recycling during operation. Further, porous granular materials are especially suited for liquid type aerosols or to the presence of high humidities where fiber filters clog rapidly. The major experimental studies of fluidized beds for particulate filtration are reviewed in the next section.

EXPERIMENTAL STUDIES OF FLUID BEDS

Conventional Fluidized Beds

References 1-10 present the major studies that have been performed on aerosol filtration by conventional fluidized beds.

Meissner and Mickley[1/] conducted laboratory studies of sulfuric acid mist removal via fluidized beds. Exploratory runs on the removal of ammonium nitrate dust were also conducted. The experimental studies covered the collection of sulfuric acid mist droplets, 2-14 µm in diameter, with fluid beds of glass beads, silica (both nonporous), alumina and silica gel (both porous), and aluminum silicate. Using a 4.7 cm diameter glass column, 1.2 m high, these investigators found that for particles in the micron range (~8 µm) an empirical equation of the form

$$\ln \frac{C_2}{C_1} = -Kv_g w^n \qquad \text{(H-1) (1)}$$

could be fitted to their limited data. In Eq. (1)

C_1 = inlet concentration

C_2 = outlet concentration

K = 0.142

v_g = superficial velocity (ft/sec)

w = bed weight/unit area (lb/ft^2)

n = empirical constant which varied from 0.157 to 0.34 depending upon type of bed material.

Collection efficiencies up to 93% were obtained in the tests, and the authors stated that with optimum design, higher efficiency might be attained.

Scott and Guthrie[2/] conducted studies with fluidized beds using dioctyl phthalate droplets (0.5-1.1 μm). The average droplet diameter in all runs was 0.87 μm. Scott and Guthrie found that removal efficiencies were only slightly affected by a 50% change in inlet mist concentration or by variations in the weight of bed solids per unit cross sectional area of bed. Collection efficiencies varied from 70% at high superficial velocities to 90% at low velocities. Scott and Guthrie reported that their data could be correlated by an equation of the form

$$\ln \frac{C_1}{C_2} = K v_g^{-0.78} \qquad \text{(H-2)}$$

In the studies reported in Refs. 1 and 2, it was found that the collection efficiency was independent of the inlet concentration. For the larger droplets (2 to 14 microns) inertial impaction appeared to be the predominant collection mechanism, efficiency improving with increasing superficial gas velocity. For the smaller dioctyl phthalate droplets, diffusion collection predominated, as was shown by the opposite trend of a decreasing efficiency with increasing superficial gas velocity.

Black[4/] has conducted one of the more detailed studies of fluid beds as particulate filters. The purpose of his work was to investigate the factors contributing to removal efficiencies of small diameter aerosols in a bed of fluidized glass shot. A column geometry was chosen for the study. Figure H-1 presents a schematic of the apparatus used in the investigation.

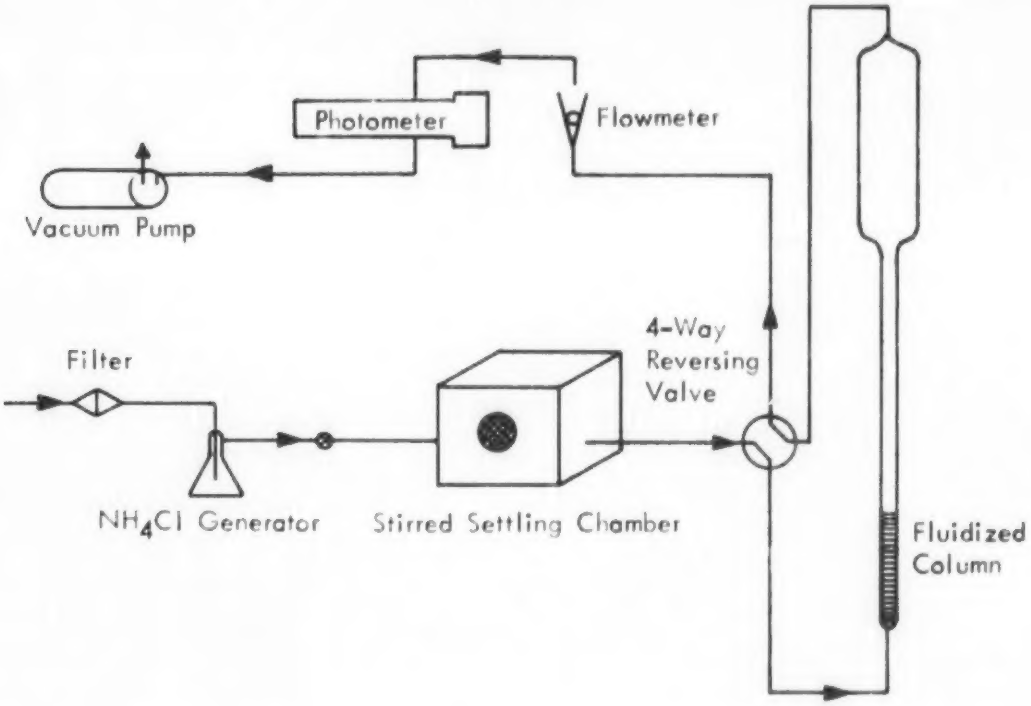

Figure H-1. Schematic flow diagram of Black's fluid bed system

In Black's experimental program, the effectiveness of a fluidized bed in removing airborne particulate from an air stream was investigated at superficial gas velocities of 2.7 to 7.6 m/min. Lower velocities were insufficient to fluidize the bed material, while higher velocities resulted in excessive bed carry-over. Bed height-to-diameter ratios were varied from two to six. The aerosols chosen were ammonium chloride and tobacco smoke. Concentration of aerosol ranged from 0.03 to 8.3 mg/cu m. Ambient temperature conditions prevailed, normally 20°C to 30°C.

Light field microscopy was used to determine the inlet aerosol particle size distribution for ammonium chloride, the mean size with respect to count was 0.52 micron with a geometric deviation of 2.32. Mean size with respect to mass was 4.3 microns. Tobacco smoke was determined by light field microscopy to have a mean size of 0.35 micron. However, it is felt that this determination was too low since water and certain soluble organics which surrounded the tobacco particle did not show up in the method of microscopy. Tobacco smoke particle diameter was estimated to be the same as ammonium chloride particles, inasmuch as filtration efficiencies were almost exactly the same under the same conditions of operating variables.

Filtration efficiencies of the fluidized bed in removing either ammonium chloride or tobacco particles of submicron size ranged from approximately 50 to 90% on a count basis. Lowest efficiencies were encountered at highest gas flow rates and lowest bed heights. Highest efficiencies resulted from low gas flow rates and high bed heights. No effective change in filtration efficiencies of the fluidized bed were found as a result of bed age or changes in inlet aerosol concentration. Black reported that the following equation could fit the data for all runs within experimental accuracies:

$$\eta = 0.565 \frac{h^{0.4}}{v_g^{0.1}} \qquad \text{(H-3)}$$

where η = collection efficiency, h is the bed height-to-diameter ratio, and v_g is the superficial gas velocity. Over 90% of measured efficiency values are within 5% of values predicted by Eq. H-(3). Figure H-2 indicates pressure drops for several different bed heights as a function of gas flow rates.

The pressure drop across the filtration system does not change radically with changes in gas velocity, and changes in gas velocity do not have appreciable effect on filtration efficiencies. This is not true with many filtration systems.

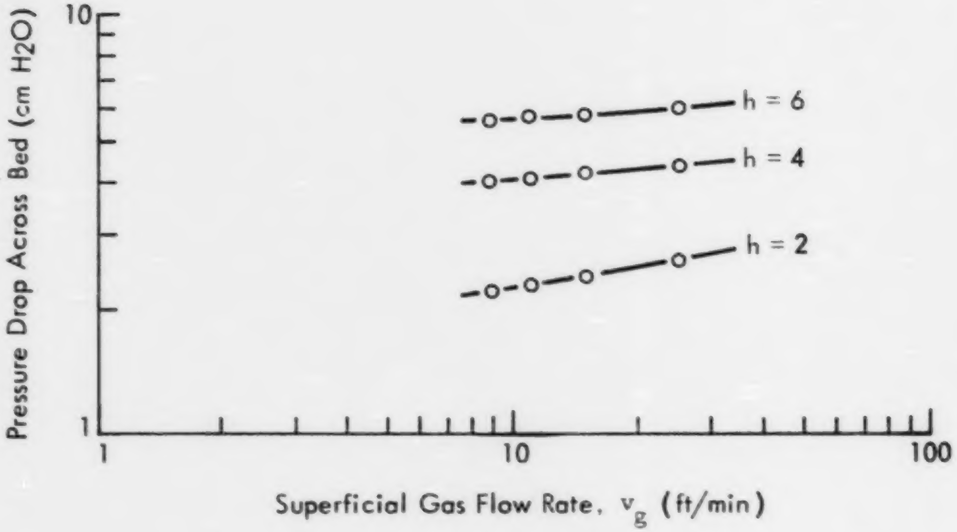

Figure H-2. Results of pressure drop measurements across fluidized bed at various gas flow rates and bed heights

Analysis of possible filtration mechanisms that might be effective in his system, led Black to conclude that interception, supplemented by Brownian diffusion, was the dominant mechanism. Using variables suggested by Friedlander's equation for effective filter efficiency with combined effects of interception and Brownian diffusion gives

$$\eta = \frac{6(N_R N_{Pe}{}^{1/3} N_{Re}{}^{1/6}) + 3(N_R N_{Pe}{}^{1/3} N_{Re}{}^{1/6})^3}{N_R N_{Pe}} \qquad \text{(H-4)}$$

Data for the various bed height-to-diameter values (h) used in the study were plotted as shown in Figure H-3. The curves in Figure H-3 can be represented by Eq. (H-5).

$$\eta = \frac{(N_{Pe}{}^{1/3} N_{Re}{}^{1/6} N_R)^{1.78} (h)^{0.4} 5.1 \times 10^4}{(N_R N_{Pe})} \qquad \text{(H-5)}$$

The slope of the curve for pure diffusion (Equation H-4) is one while the slope of the curve for pure interception is three. The fact that the slope of the lines in Figure H-3 is between one and three implies both Brownian diffusive and interceptive forces are active in the fluidized bed used by Black.

The experimental conditions selected in the studies reported in Refs. 1, 2, and 4 emphasized different collection mechanisms. The major differences between the work of Meissner and Mickley and that of Black or Scott and Guthrie is that the average particulate mass used in the work of the latter investigators was two to three orders of magnitude smaller than that used by Meissner and Mickley. As a result, inertial forces were more important in the experiments of Meissner and Mickley, while diffusion and/or interception were the controlling mechanisms in the other experimental configurations.

Jackson and coworkers have recently reported results of a study to compare directly the collection of fine particles by a bed of granules operating in both the fixed and fluidized states. Monodispersed aerosols of dioctyl phthalate, in sizes of 0.67 and 1.2 microns were collected in a bed of granules of porous activated alumina having a mean size of 175 microns. Collection efficiency was determined by simultaneous measurements of laser

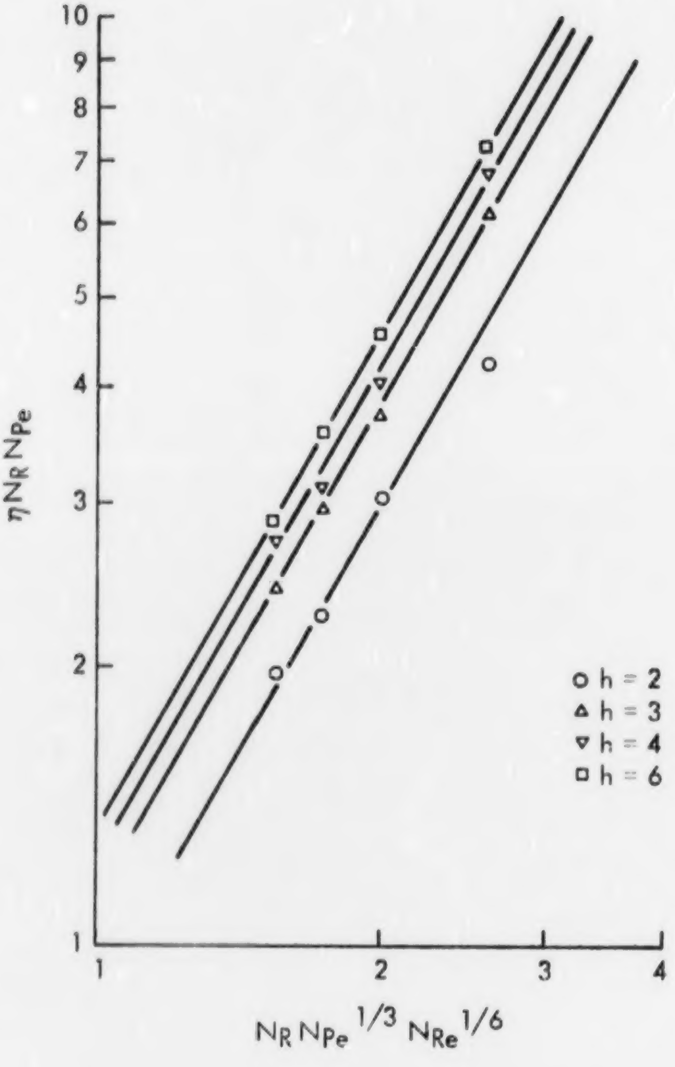

Figure H-3. Collection efficiencies in fluidized beds light attenuation by inlet and outlet streams. A nuclei particle counter confirmed results. Bed depths of 2.5-10.1 cm resulted in collections up to and exceeding 99% in the fixed state for either particle size; efficiencies dropped markedly upon bed fluidization and with increasing gas velocity to 70-80% at twice the initial fluidization velocity. The data of Yankel, smoothed and adjusted for the region approaching 100%, are shown in Figure H-4.[6] The bed held 7% DOP before freezing.

Reference 7 discusses some alternative bed designs which permit periodic collapse of bubbles and mixing to increase collection. Arrangements to provide multiple contact of gas flow and collecting granules include use of either multiple beds (stacked) in series or perforated plates or other devices within a single bed.

Attainment of high efficiencies by staging may be possible even though single stage efficiencies are not high. Assuming complete mixing between stages, the collection by "n" stages would give an outlet concentration of particles of

$$C_2 = C_1 (1 - E')^n = C_1 P^n \qquad \text{(H-6)}$$

where E' is the fractional efficiency per stage, $P = (1 - E')$ is the penetration per stage, and C_1, C_2 represent the inlet and outlet concentrations. The overall collection efficiency is:

$$\% = 100 (C_1 - C_2)/C_1 = 100 (1 - P^n) \qquad \text{(H-7)}$$

For various combinations of stage efficiency, number of stages, bed depths, and for a gas velocity (20 cm/sec) twice the initial fluidization velocity (see Figure H-4 and 0.67 micron size aerosol, the total collection efficiencies are given in Table H-1. Because the pressure loss across a fluidized bed is less in inches of water than the depth for most materials, (n x bed depth) gives a measure of the energy consumption. From Table H-1, the very shallow 2.5 cm bed at five stages, and less than 13 cm of water pressure drop, gives the same very high collection as four stages of 5.1 cm bed and three stages of a 7.6 cm bed. Other pressure losses may occur between stages and an optimization analysis between collection efficiency and energy loss is indicated.

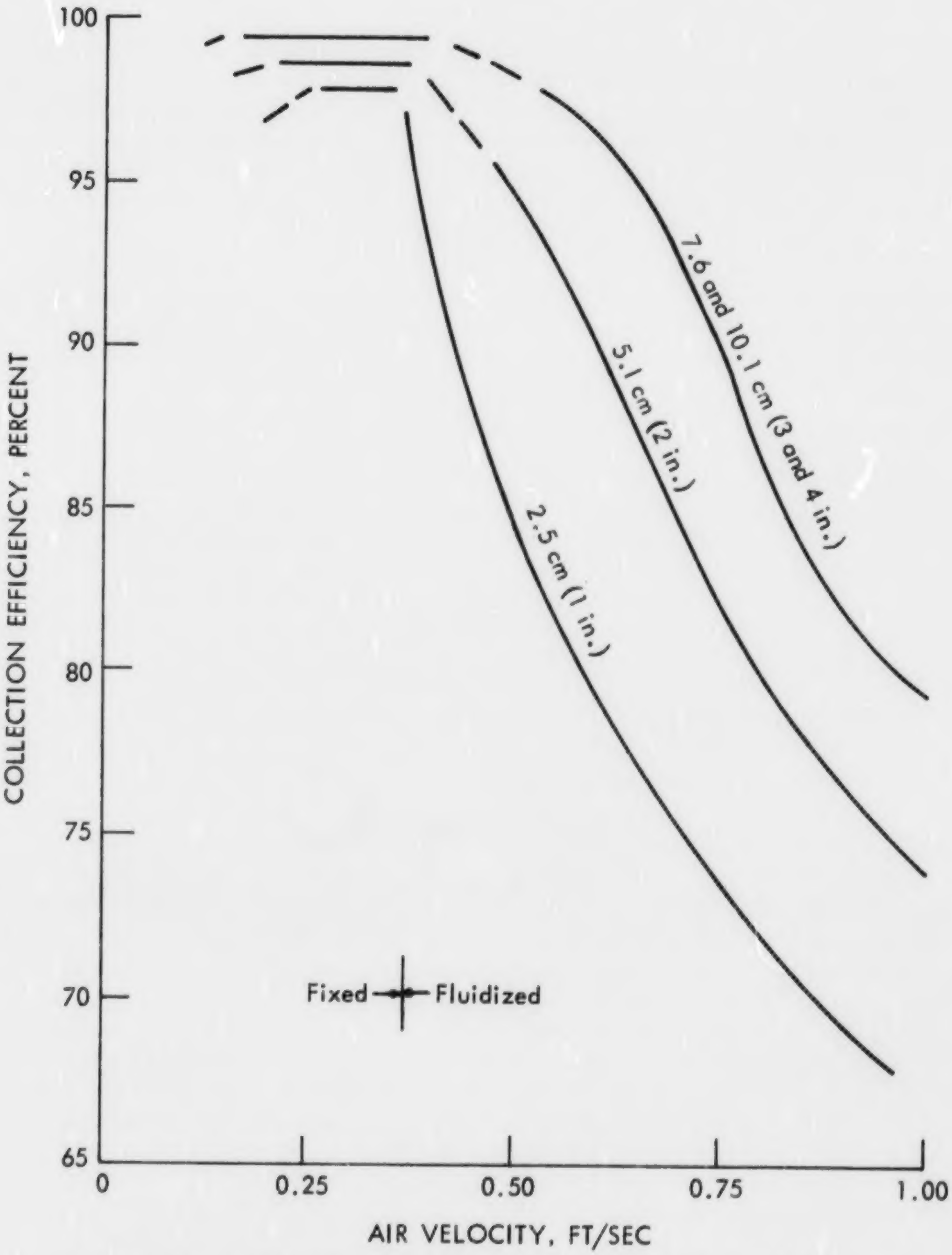

Figure H-4. Collection of 0.67 μm DOP aerosol by beds of 175 μm alumina granules

Table H-1. ESTIMATED COLLECTION BY MULTIPLE-CONTACT FLUIDIZED BEDS[7]

Number of Stages	2.5 cm (1 in.) Bed (E' = 0.72) (%)	5.1 cm (2 in.) Bed (E' = 0.77) (%)	7.6 cm (3 in.) Bed (E' = 0.85) (%)
1	72.0	77.0	85.0
2	92.2	94.7	97.8
3	97.8	98.8	99.7
4	99.4	99.7	99.9
5	99.8	99.9	99.99

Equation H-7 is valid providing that the collection efficiency on each stage does not vary with changes in aerosol concentration. Available data reported in Refs. 2 and 4 indicate that collection efficiency is not dependent upon aerosol concentration. Scott and Guthrie report only a slight influence of aerosol concentration on efficiency for changes in concentration up to 50%.[2] Black[4] reports no effect for concentrations ranging from 1 to 75 x 10^{-4} gm/m^3.

The main observations from previous work on fluid beds are:

1. The efficiency of collection in a fluid bed is dependent upon the size of the particles to be collected, gas velocity, particle density, and size of the collecting surface.

2. Collection efficiencies in fluid beds are not affected significantly by variations in inlet grain loadings.

3. Single-pass fluidized beds of granules inherently show low collection efficiencies because of the passage of gas bubbles through the bed.

4. Fluidized beds may provide very high collection efficiencies when employed in a multistage arrangement or with an internal bed structure that collapses and reforms gas bubbles.

5. Pressure drops through the fluid beds used in previous experimental work ranged from about 1.0 to 20 cm H_2O which is no greater than that through other devices of comparable efficiency.

6. Large gas volumes can be handled, though linear bed velocities may only range from 0.3-0.6 m/sec (1-2 ft/sec), by use of larger bed areas such as in drying operations which use fluidized beds.

7. Fluid beds have no specific limitation with respect to temperature, and they could be operated continuously and the bed solids regenerated.

Electrostatic Augmented Fluidized Beds

The mechanisms involved in electrostatic filtration of aerosols in fixed and fluidized granular beds were studied at the Air Cleaning Laboratory at Harvard University from 1955 to 1958.[8] Polystyrene spheres were used as the granular media in these studies. Polystyrene granules were charged *in situ* by means of interspersed wires in the filter matrix or were remotely charged using a vibrating cylindrical Lucite trough. The test aerosol of gentian violet microspheres was charged to 18-64 electron charges (positive)/ particle by a spinning disc generator. A fixed bed of polystyrene granules (280 micron diameter) with a surface charge density of 0.09 esu/cm^2 had a 64% collection efficiency for atmospheric dust as compared with a 96% efficiency for a fluidized bed expanded to 120% of the original bed depth.[8]

Studies were also conducted on beds of heated and unheated polystyrene. Polystyrene granules possess an intrinsic bipolar charge at zero net levels, and an added net charge acquired by triboelectrification. Both charges increase filtration performance. Heating for 2 hr at 80°C causes the granules to reverse their charges; mixed beds of heated and unheated materials have decided bipolar effects. Calculations indicated that a fluidized bed of heated and unheated polystyrene granules will filter five times as efficiently (based on target efficiency) as a bed of grounded conducting media, handling over two times as much air volume at equivalent flow resistance.[8]

Professor Melcher and his colleagues at MIT have recently proposed the use of electrofluidized beds for the collection of submicron particulates as an outgrowth of work on charged droplet scrubbing.[10] Figure H-5 presents a schematic diagram of an electrofluidized bed which might be used for the collection of oil ash particulate. The electrofluidized bed is composed of oil ash particulate that has achieved the size range of 50-100 microns. These particles exist in a fluidized state with the stack gas providing the fluidization. Electrodes are used to impose an electric field that serves not to collect particles but rather to charge the collection sites.

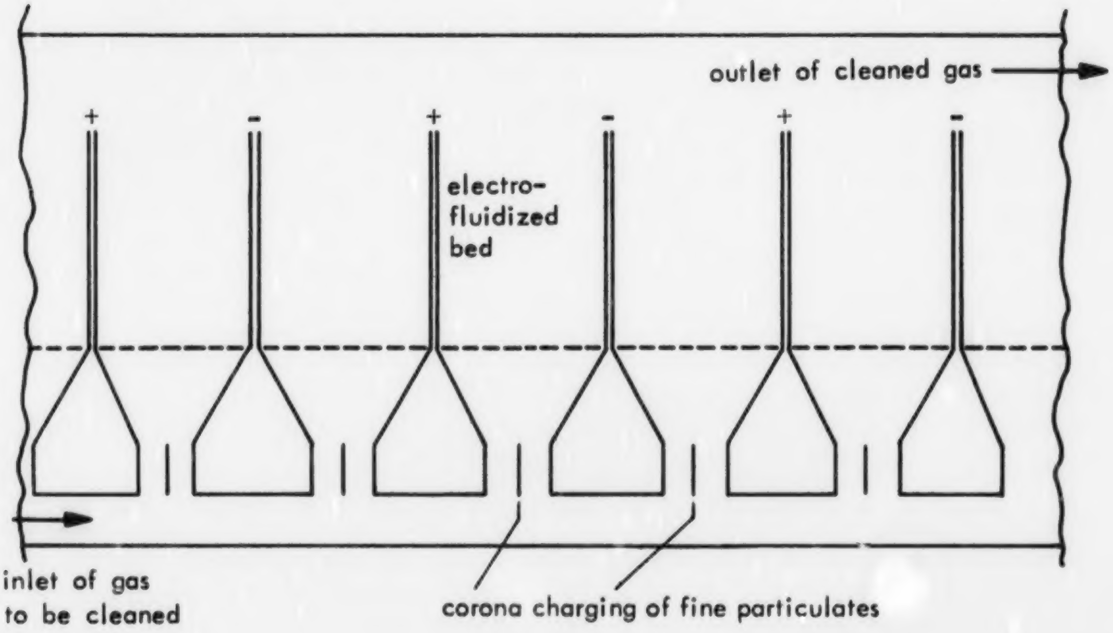

Figure H-5. Possible configuration for electrofluidized bed, typical of application to cleaning of oil ash[10]

Start-up of the system would be accomplished by seeding the bed with particles which are either externally "manufactured" or residual from previous operation of the bed. The fine particulate enters the fluidized region after having been charged in a conventional corona charging section. On passing through the fluidized bed, agglomeration is electrostatically induced with the large particles. The large particles are withdrawn from the bed at a relatively slow rate so as to insure that the agglomeration will itself retain the required population of collection sites. Thus the final form of collection is in relatively large particulate (50-100 μm range) withdrawn in a fluidized state from the bed.

Although it is too early to assess its ultimate utility in the control of particulates from industrial sources, the electrofluidized bed offers an interesting approach to control of fine particulates which is worthy of some additional investigation.

CONCLUSIONS

The capability of fluid beds to remove dusts and mists from gas streams has been studied only to a limited extent and their potential as particulate filters has not been completely characterized. Multistage systems might provide high collection efficiencies, but operational problems involving bed regeneration and attrition are anticipated. Additional work on conventional fluid beds is not recommended.

Fluidized beds augmented by electrostatic forces appear to be more effective for the removal of particulates than are conventional fluidized beds. Additional analysis of the feasibility of augmented fluid beds is recommended in conjunction with a general detailed assessment of electrified filters.

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APPENDIX I

GAMMA-RAY PRECIPITATORS AS PARTICULATE CONTROL DEVICES

INTRODUCTION

The idea of utilizing ionizing radiation to charge particulate matter so that it could be collected by electric fields in an electrostatic precipitator has been proposed in the patent literature.[1-3] Schmidt has recently proposed the use of gamma-ray ionization to charge particles and has proposed the development of particulate collection devices utilizing gamma-ray ionization.[4] Available theoretical and experimental information on this concept is reviewed in the following sections.

THEORETICAL ASPECTS

In a radiation-induced precipitator, electrons and positive ions are produced throughout the volume of the conduit by gamma rays interacting with the walls and gas (Figure I-1). Several processes are involved. Photoemission can take place at the walls, freeing large numbers of electrons. Direct ionization of the gas can take place; recombination of electrons and positive ions can occur in this high pressure, low temperature plasma system; the dust particles themselves can be ionized by direct gamma-ray interaction, etc. Electrons have a tendency to combine with polar and electronegative gases present in the air, such as SO_2, H_2O and O_2. These form negative ions, which are 1,000 times less mobile than electrons, and tend to recombine with, and neutralize, the positive charges. Space charge separation combined with photoemission may occur. These effects are represented in Figure I-2.

Photoemission of electrons from the anode, traveling against the field, could contribute to the negative part of the space charge, while photoemission from the cathode, in the direction of the field, could further energize the electrons, thereby reducing their recombining potential in the positive space charge section.

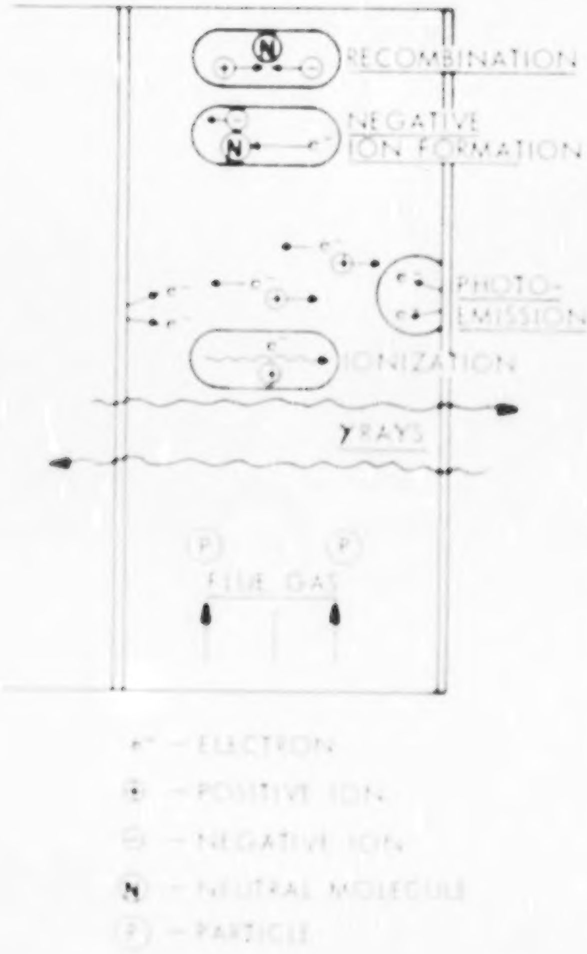

Figure I-1. Reactions occurring in the radiation-induced precipitator

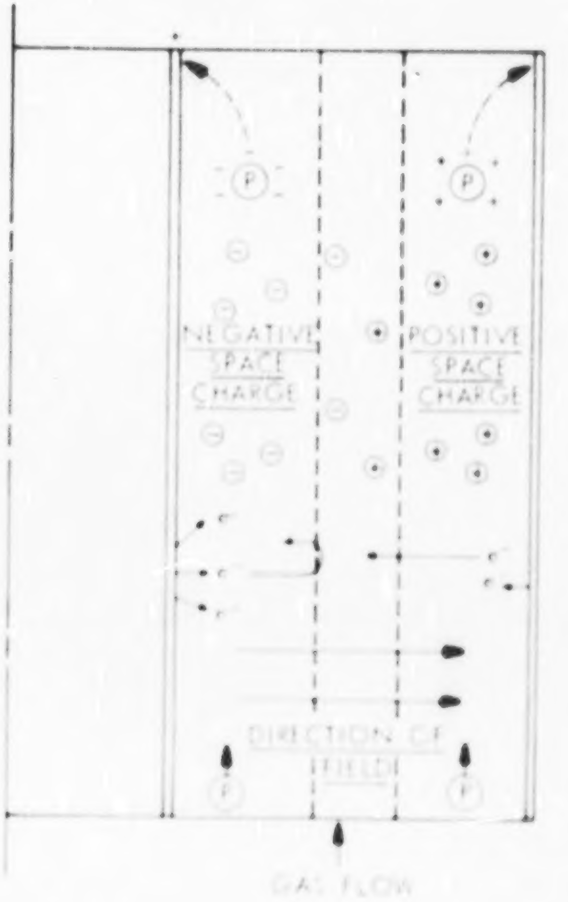

Figure I-2. Space charge separation and particle charging in radiation-induced precipitator

Particles entering the ion-filled region become charged by field charging and diffusion charging. The charging processes are identical to those that occur in a conventional electrostatic precipitator. The charged particles then would enter an electric field and be collected in the usual manner of an electrostatic precipitator.

EXPERIMENTAL INVESTIGATIONS

Experimental studies of the gamma-ray precipitator concept have been conducted at Penn State University using the experimental system shown in Figure I-3.[5-7] A small coal burning stoker-fed home-type furnace was installed adjacent to the cobalt pool of the reactor facility. The particulate and combustion products from the furnace travel upward to a cast iron flue pipe assembly. This assembly contained by pass regulating dampers and sampling ports. The sampling ports were used to extract gas and particulate samples and to measure gas temperature. The precipitator section was a coaxial aluminum pipe section whose inner pipe was 12.7 cm ID and whose outer pipe was 20.3 cm ID. This section was insulated electrically from the remainder of the system by a Teflon ring arrangement at the top and three standoff insulators located halfway down the precipitator section.[6]

Flue gas proceeded down the center pipe, turned around, and went up the outer sleeve and, ultimately, to the blower and stack. The gas flow rates used were in the range of commercially used value of 1.2-4.6 m/sec (4-15 ft/sec). Most of the experiments were run at 1.5 m/sec (5 ft/sec)

Irradiation occurred at the bottom turn around area of the precipitator section. The ^{60}Co sources were in the form of pencils, doubly encapsulated in stainless-steel tubes, 1.3 cm in diameter x 30.5 cm long. The pencils were arranged in a horseshoe-shaped holder on top of a movable platform. The platform could be positioned to have the horseshoe encircle the large aluminum pipe, or it could be moved away to reduce the field by given amounts. The shielding for the cobalt pencils was 4.3 m (14 ft) of water.[6]

A 50,000-V, 5mA power supply was mounted on the scaffolding, and the electrical connections were such that the inner pipe could be made either positive or negative with respect to the outer pipe. The outer pipe was always grounded.[6]

Figure I-4 shows the overall efficiency of the device described in Figure I-3 as a function of central electrode potential. Efficiences were obtained from gross filter samples taken at the inlet and outlet of the precipitator. The efficiency at zero kV represents mechanical removal,

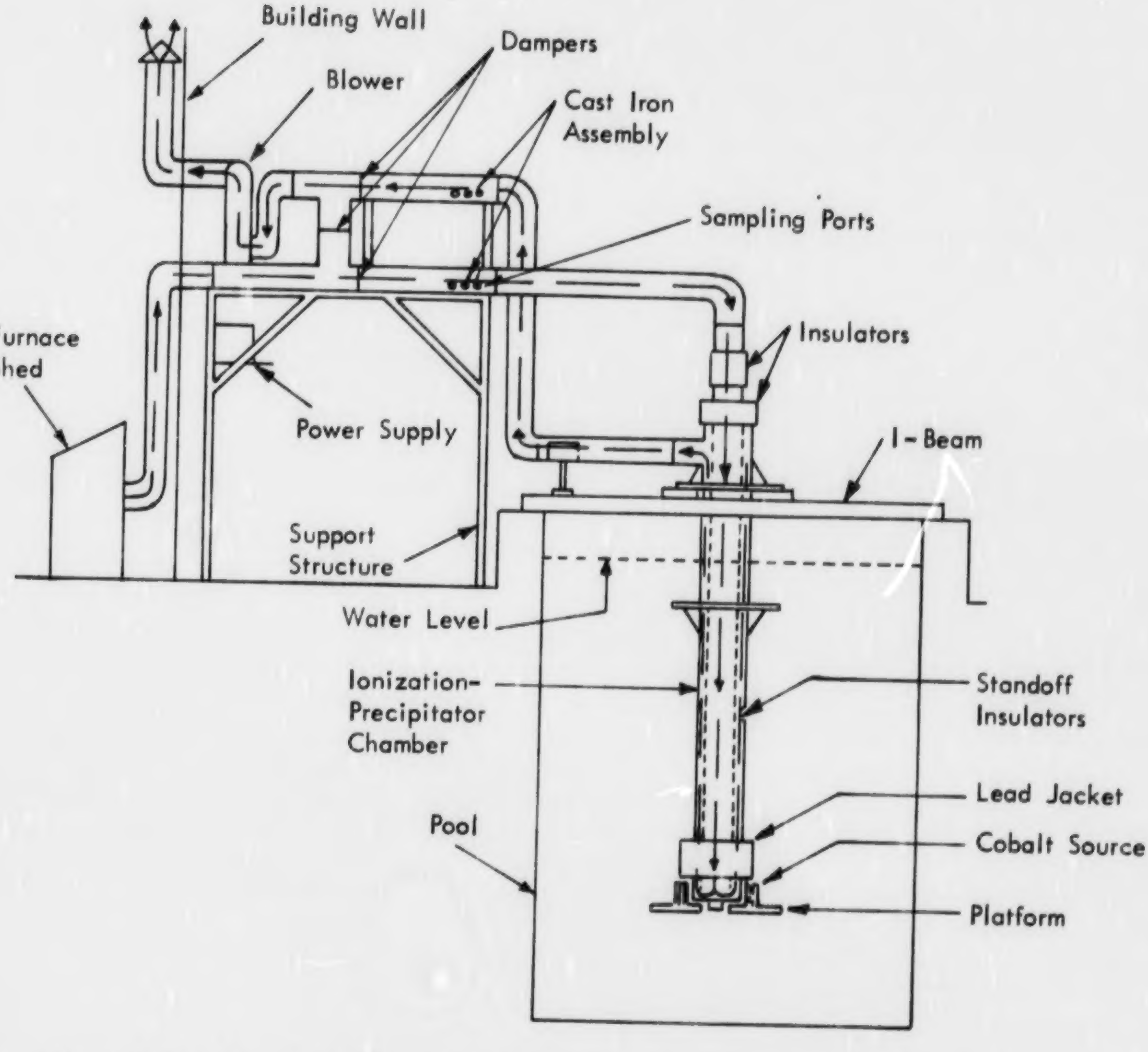

Figure I-3. Schematic diagram of gamma-ray precipitator and auxiliary equipment at Pennsylvania State University

mostly of larger-sized particles. Error bars indicate data points where multiple samples were taken and standard deviations calculated.

Figure I-4 also indicates no change in efficiency when the polarity of the central electrode is changed. The efficiency in both cases for this single stage device is approximately 96% with an applied potential of 27 kV across the precipitator tube.

Figure I-5 shows the importance of dose rate applied to the charging region of the precipitator for one run. The maximum dose was used in all other experiments.

Cascade impactor samples were used to study precipitator performance as a function of particle size distribution. A typical incoming concentration of fly ash from the furnace is shown in Table I-1. These values show a high proportion of small particles indicating a larger percentage of small particles than exists in most coal-burning commercial stacks.

Table I-1. TYPICAL PARTICLE CONCENTRATION AT INLET TO GAMMA-RAY PRECIPITATOR (20-ft^3 sample)

Mean Diameter (μm)	mg/ft^3	Percent of Total by Weight	Number (cm^3)	Percent of Total by Number
0.4 or smaller	1.27	48.9	6.8×10^3	98.8
1.1	0.30	11.5	7.7×10^3	1.1
1.8	0.11	4.4	6.6×10^2	0.094
2.7	0.10	3.8	1.7×10^2	0.026
3.8	0.14	5.4	8.7×10	0.013
5.4 or smaller	0.68	26.1	1.5×10^2	0.021

Figure I-6 presents fractional efficiency data for the device. The fractional efficiency of the device is about the same as that for a high efficiency electrostatic precipitator.

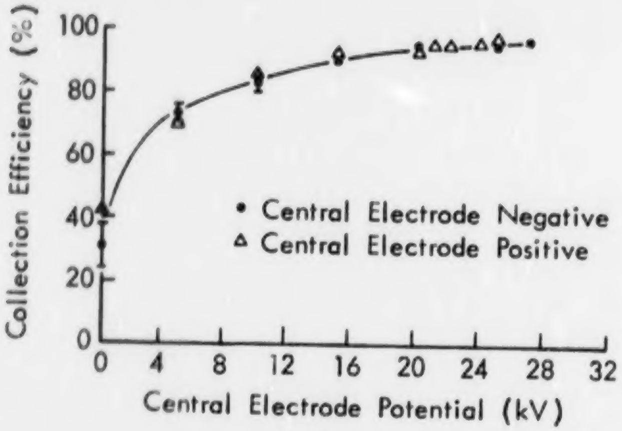

Figure I-4. Collection efficiency of gamma-ray precipitator vs central electrode potential based on weight percent of inlet particulate concentration

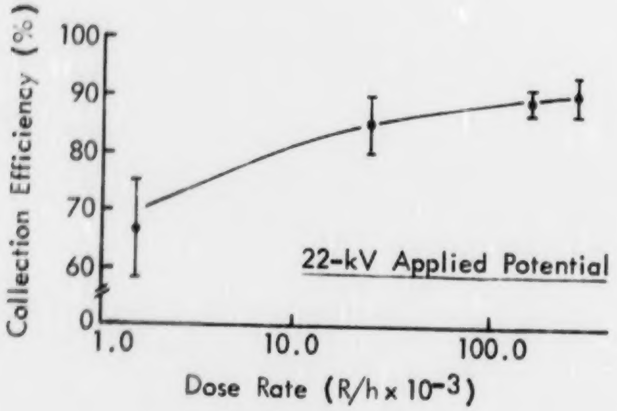

Figure I-5. Collection efficiency of gamma-ray precipitator vs dose rate

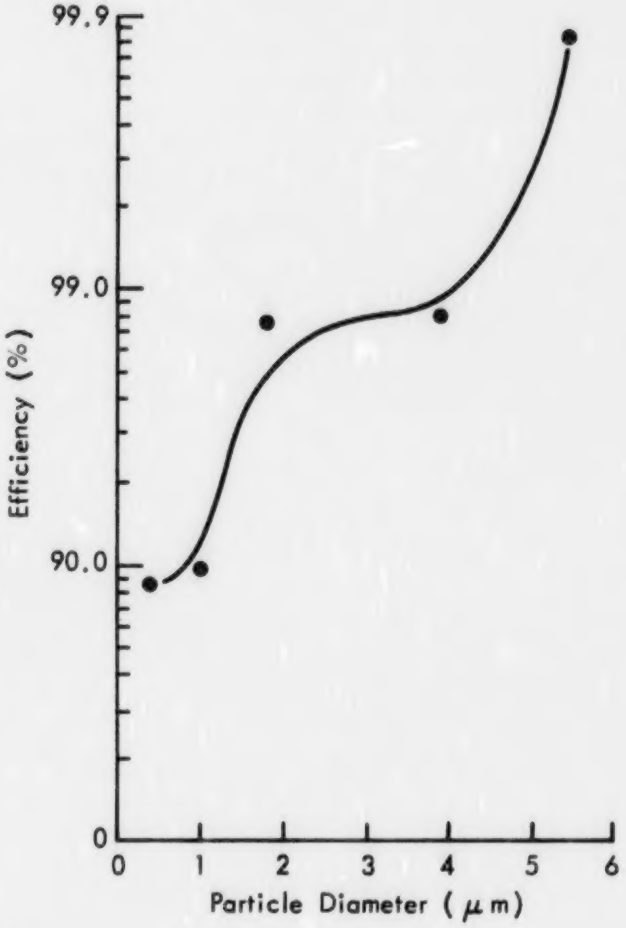

Figure I-6. Experimental fractional efficiencies of gamma-ray precipitator

CONCLUSIONS

Definitive conclusions regarding the potential of the gamma precipitator cannot be reached at this time. Only limited test data on a nonrepresentative source are available. However, the results of the limited tests indicate collection efficiencies comparable to those conventional electrostatic precipitators.

The gamma ray precipitator has the following possible advantages in comparison to conventional electrostatic precipitators: (a) possible higher ion densities; (b) lower operating costs; and (c) simplified cleaning.

The major disadvantages are the radioactive material required and the shielding structures. Both of these disadvantages will greatly limit the use of such a device even if it were proven highly efficient. Utility companies with experience in handling nuclear materials would appear to be the only likely applications for such a device.

On balance, the disadvantages of a gamma ray precipitator far surpass the advantages. Development of this device is not warranted in our opinion.

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